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HANDBOOK OF AEROSPACE AND OPERATIONAL PHYSIOLOGY

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Final Report
for September 2006 to January 2011

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14. ABSTRACT
This handbook is designed to be a reference for aerospace physiologists and technicians in the U.S. Air Force. It contains information about physiologic principles and application of those principles to Air Force flight operations. While it is not designed to be a clinical resource, references to clinical materials are provided to allow further study. The first two sections contain information on basic human physiology and Earth's atmosphere pertinent to the field of aerospace physiology. Section 3 reviews the environmental effects of the atmosphere, and Section 4 addresses human performance. Sections 5-7 address aircraft systems, crewmembers' personal equipment, and the mission-imposed effects on performance and survivability. Section 8 reviews training, activities, and resources needed for aerospace physiologists to accomplish their duties. The appendices provide reference tables and procedures related to the career field and short biographies of the contributing authors/subject matter experts.

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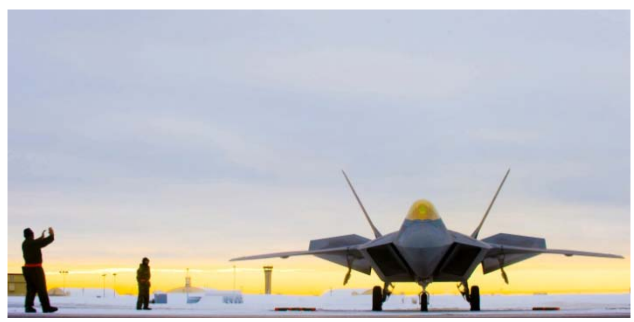

PREFACE

The purpose of this document is to provide a resource for information about physiologic principles and application of those principles pertinent to aerospace physiologists and technicians in the U.S. Air Force. While it is not designed to be a clinical resource, many references to clinical texts and articles are provided to allow further study.

The scope will likely challenge those without some familiarity with crewmember personal equipment capabilities and limitations or without any human physiology background. Without such a challenge, it would be of little use to many who need a reference relevant to their work.

The sequence of sections is meant to introduce pertinent human physiology, the atmosphere, and effects of the atmosphere on human physiology. The section on human performance enhancement requires an understanding of human physiology covered earlier in the document and of human factors, which is emphasized in this and following sections. The next sections describe how the various Air Force aircraft systems, personal equipment, and missions interact with the individual to both limit and enhance optimal function. Background information is provided on aircraft systems and personal equipment design, function, and limitations. Aerospace physiologist training, evaluation, activities, and resources complete the body of this reference document.

Appendices 1 and 2 altitudes vs. pressure and oxygen levels as well as conversion tables are relevant to several sections, and their placement is meant to provide a common reference and avoid duplication. Appendix 8 contains URLs for internet resources that are followed by the subject description and last date checked for viability. Organizations of potential interest to aerospace physiologists follow with questions on each section. The last appendix contains short biographies of the contributors to this document.

The objectives listed at the beginning of most sections are for AFI 11-403 Original Course instructor use in developing presentation materials and background study.

Lt Col Andrew D. Woodrow and James T. Webb, Ph.D.

HISTORY

Since the 17th century, many findings and inventions have allowed discoveries of the properties of the atmosphere and space. The problems of hypoxia, trapped gas expansion, decompression sickness, and ebullism were discovered, endured, addressed, and sometimes ignored with unfortunate consequences. To understand the problems associated with reduced atmospheric pressure, many physiologists, physicists, and physicians labored to quantify properties of the atmosphere. Their formulation of gas laws and descriptions of atmospheric characteristics enabled physiologists, physicians, inventors, and designers to investigate atmospheric effects and conceive mechanisms to enable safe passage into these realms. Better design of air and spacecraft, personal protective equipment, and procedures to protect the crew and passengers have saved many lives and enhanced mission effectiveness and capabilities. Establishment of the Physiological Research Laboratory at Wright Field, OH, on 29 May 1935 ushered in an era of historic research and achievements, largely through the efforts of Captain Harry G. Armstrong. Some highlights of some of these and other achievements in aerospace physiology are presented in many sections.

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1. HUMAN PHYSIOLOGY

Organ systems of the human body are susceptible to the effects of aerospace environmental stressors. Knowledge of these systems is necessary to understand how changes in environmental conditions can produce serious hazards to human performance and survival. Using the basic knowledge of physiology presented here and of the aerospace environment, researchers, engineers, physicians, and aerospace physiologists have played critical roles in the design of aircraft systems, personal protective equipment, and procedures. The results of their efforts have reduced or eliminated most environmental threats to aircrew by innovations and improvements in aircrew equipment and procedures.

1.1. Circulation

Col Paul W. Fisher, USAF, BSC

The human circulatory system is a closed, continuous loop system that can be divided into two subdivisions or circuits: the pulmonary circulation and the systemic circulation. It is composed of the blood, the heart, and the conducting vessels: arteries, arterioles, capillaries, venules, and veins. Its primary function is to serve as the transportation system within the body, but it also contributes to other functions such as thermoregulation; water, electrolyte, and pH balance; and defense against pathogens.

1.1.1. The Blood

The blood is the transport vehicle of the cardiovascular system.

The blood transports nearly everything that must be carried from one place to another within the body (Marieb &Hoehn, 2007, p. 647). The blood is the only fluid tissue in the body and is composed of both cellular and liquid components. If a blood sample is spun in a centrifuge, the heavier formed elements will be packed at the bottom of the centrifuge tube with the less dense fluid plasma at the top (Fig. 1.1.1-1). The red mass at the bottom of the tube is primarily erythrocytes, the red blood cells responsible for transporting oxygen. Red blood cells (RBCs) are the most abundant cell type in the body and make up approximately 45% of the total blood volume. Each mL of blood contains 5,200,000 ± 300,000 RBCs (Guyton and Hall, 2000, p. 382). An average man with a total blood volume of about 5 L has approximately 26 billion RBCs circulating throughout his body. The normal percentage of RBCs, the hematocrit, varies somewhat between men and women, with males having a value of 47% ± 5% and females 42% ± 5% (Marieb & Hoehn, 2007, p. 648). Hematocrit also varies with environmental and physiologic stressors such as prolonged exposure to altitude. Above the RBCs in the centrifuge tube is a thin whitish layer that contains leukocytes, white blood cells involved in the body's immune response, and platelets, cell fragments critical to the blood clotting process. Leukocytes and platelets contribute less than 1% of blood volume, with plasma making up the remaining 55%.

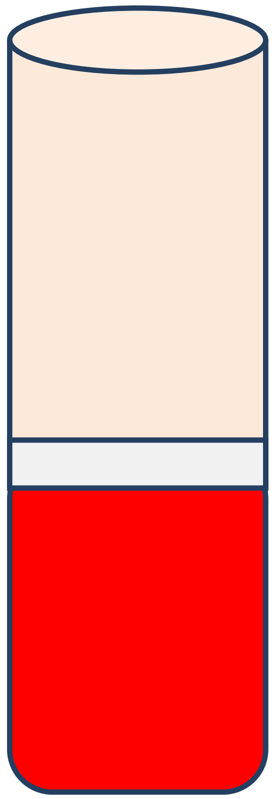

Figure 1.1.1-1. A Blood Sample Spun in a Centrifuge Tube Will Separate into Key Components

Plasma, the fluid matrix of the blood, is 90% water but contains over 100 dissolved solutes (Marieb & Hoehn, 2007, p. 648). Plasma proteins, most of which are produced by the liver, are the most abundant plasma solutes. They perform many functions, but of particular interest to us is their contribution to the blood's osmotic pressure, which is critical in maintaining the water balance between the blood and the tissues. Other solutes of interest include by-products of cellular respiration such as urea, uric acid, and creatinine; nutrients absorbed from the digestive tract including glucose, amino acids, fatty acids, cholesterol, and vitamins; electrolytes such as sodium, potassium, calcium, chloride, phosphate, and bicarbonate; the respiratory gases, oxygen, carbon dioxide, and nitrogen; and hormones.

1.1.2. Erythrocytes

Erythrocytes are of particular interest to the aerospace physiologist because of their role in the transport of respiratory gases. RBCs are small, about 7.5 µm in diameter, biconcave disc-shaped cells (Marieb & Hoehn, 2007, p. 649); that is, they are flattened discs with depressed centers (Fig. 1.1.2-1). Although RBCs assume this basic shape, they are highly deformable, allowing them to squeeze through small blood vessels without rupturing. When mature, human RBCs lack a nucleus and other internal organelles. They are essentially bags of hemoglobin, the protein responsible for gas transport and the protein that gives them their red color. Because mature RBCs lack a nucleus and other internal organelles, they are unable to synthesize new proteins for growth, repair, or cell division. As a result they age rapidly. Within 100 to 120 days they become rigid, their hemoglobin begins to degenerate, and they are

removed from the circulation. Most of their proteins and other constituents are broken down and recycled. New RBCs are produced by division of stem cells in the bone marrow in a process called erythropoiesis at an incredible rate of more than 2 million per second in healthy individuals. The balance of RBC production and destruction is closely regulated, as too few RBCs leads to tissue hypoxia (oxygen deprivation) while too many increases blood viscosity, impeding circulation.

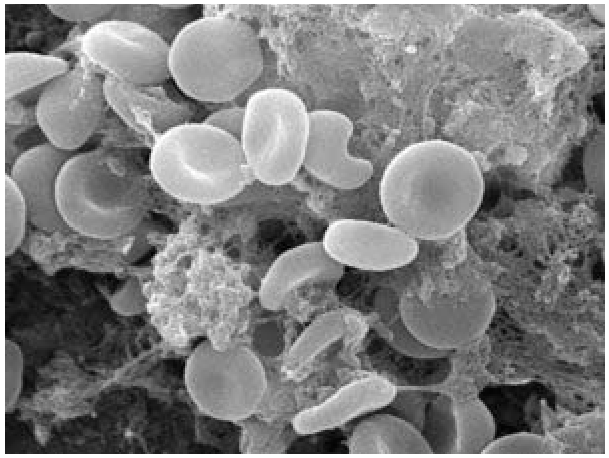

Figure 1.1.2-1. Red Blood Cells Seen Through an Electron Microscope

1.1.3. Hemoglobin

> *<u>Hemoglobin</u> is a tetrameric protein made up of four subunits: two alpha chains and two beta chains. Each subunit contains a heme pigment with a single iron atom. Each iron atom can reversibly bind a single divalent oxygen molecule (O_2); as a result, each hemoglobin molecule can bind and transport four oxygen molecules (Marieb & Hoehn, 2007, p. 650).*

A single RBC contains about 250 million hemoglobin molecules, so each cell is capable of transporting about 1 billion oxygen molecules. If we consider whole blood, typical hemoglobin concentration is about 34 gm/dL of RBCs (Guyton & Hall, 2000, p. 382). With a normal hematocrit of 45%, whole blood contains an average of 16 gm of hemoglobin per deciliter. Each gram of hemoglobin is capable of binding 1.39 mL of oxygen; therefore, each deciliter of blood is capable of carrying more than 21 mL of oxygen in combination with hemoglobin.

In addition to its oxygen-binding capability, hemoglobin can also bind and transport carbon dioxide (Marieb & Hoehn, 2007, p. 650). Carbon dioxide binds to amino acids in the globin portion of the molecule rather than the heme groups. And as is true for most proteins, hemoglobin is an excellent acid-base buffer and is responsible for most of the buffering capacity of whole blood (Guyton & Hall, 2000, p. 382).

1.1.4. Blood Abnormalities

Anemia is an abnormally low oxygen-carrying capacity of the blood (Marieb &Hoehn, 2007, p. 654). It is usually a sign of an underlying disorder rather than a disease state in and of itself. Anemia may be due to an insufficient number of RBCs, low hemoglobin content, or abnormal hemoglobin. An abnormally low RBC count can

be caused by acute or chronic blood loss (hemorrhagic anemia); excessive RBC destruction (hemolytic anemia) possibly due to hemoglobin abnormalities, certain bacterial or parasitic infections, and some toxins; or an inhibition of RBC formation in the bone marrow by certain drugs, chemicals, radiation, or viruses. Low content of normal hemoglobin in erythrocytes is typically linked to nutritional deficiencies such as a lack of iron or vitamin B_{12} in the diet, whereas production of abnormal hemoglobin usually has a genetic link. Sickle-cell anemia, for example, is due to a mutation in the gene that codes for the hemoglobin beta chain, resulting in abnormal RBC morphology and excessive RBC destruction, especially at low oxygen tensions.

In contrast to anemia, polycythemia is an abnormal excess of RBCs resulting in increased blood viscosity. Bone marrow cancer, chronic altitude sickness, and blood doping by athletes can cause abnormal polycythemia. Physiologic polycythemia is a normal response of the body to prolonged hypoxia, such as that experienced by individuals living at high altitude (Rainford & Gradwell, 2006, p. 15; Guyton & Hall, 2000, p. 390). Reduced oxygen delivery to the tissues stimulates RBC production as an adaptation to increase the oxygen-carrying capacity of the blood.

1.1.5. The Heart

The heart, about the size of a fist, lies in the mediastinum, the central cavity of the thorax behind the sternum (Marieb & Hoehn, 2007, p. 678). This hollow, cone-shaped organ weighs less than a pound yet provides the main propulsive force to circulate blood throughout the body (Fig. 1.1.5-1).

> *The heart has four chambers: two <u>atria</u> and two <u>ventricles</u>. The atria are receiving chambers for blood returning to the heart from the circulation. They are small, thin-walled chambers that do not contribute to the propulsive pumping of the blood. When they contract, they push blood into the ventricles, priming the main pumping chambers. The ventricles are much more massive than the atria and make up most of the volume of the heart; when the ventricles contract, blood is propelled out of the heart into the circulation. The right ventricle pumps blood into the pulmonary circuit while the left ventricle pumps blood into the systemic circuit. The heart can be thought of as two side-by-side pumps, each serving a separate subdivision of the circulation (or circuit). The right side of the heart is the pump for the <u>pulmonary circulation</u> (or circuit), which carries blood to and from the lungs for gas exchange. The left side of the heart propels blood through the <u>systemic circulation</u> (or circuit), which carries blood to and from all body tissues.*

Although equal volumes of blood are pumped by the right and left sides of the heart, the work load of the two ventricles is very different. The pulmonary circuit is a short, low-pressure, low-resistance circulation, whereas the systemic circuit is longer, distributing blood through the entire body; encounters five times as much resistance to blood flow; and operates at a higher pressure. As a result, the left side of the heart is a far more powerful pump, with walls three times thicker than those of the right ventricle, and is capable of generating five times greater work output (Guyton & Hall, 2000, p. 113). The heart is dependent on oxidative metabolism of fatty acids and, to a lesser extent, other nutrients such as lactate and glucose to provide the chemical energy to power the cardiac muscle (Guyton & Hall, 2000, p. 103).

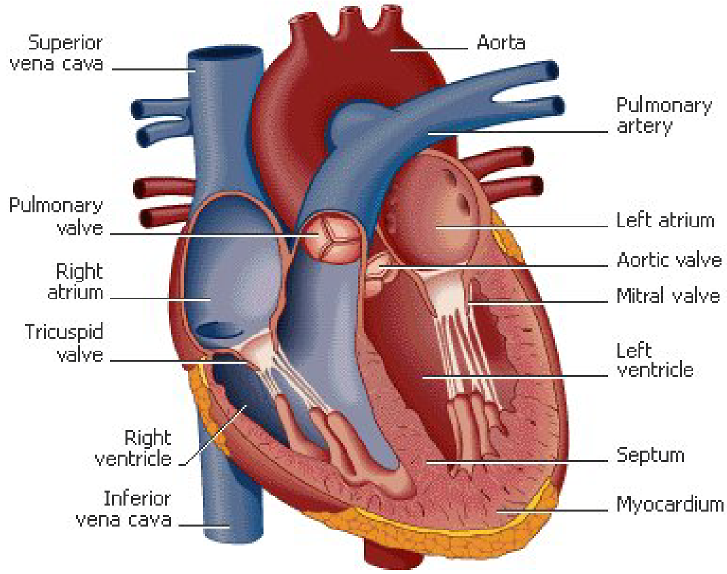

Figure 1.1.5-1. Cross Section of the Heart Showing the Atria and Ventricles, Heart Valves, and Major Blood Vessels Entering and Leaving the Heart

1.1.6. Pattern of Circulation

Blood returning to the heart from the body enters the right atrium and passes into the right ventricle. The right ventricle pumps the blood to the lungs via the pulmonary arteries. In the lungs, the blood offloads carbon dioxide and picks up oxygen, then returns to the left atrium via the pulmonary veins. Blood passes from the left atrium into the left ventricle, which pumps it into the aorta. The aorta branches into smaller systemic arteries, which distribute blood to all body tissues where gasses, nutrients, and waste products are exchanged. The blood, once again depleted of oxygen and loaded with carbon dioxide, returns through the systemic veins to the right side of the heart, entering the right atrium via the superior and inferior venae cavae (Fig. 1.1.6-1).

1.1.7. Heart Valves

This one-way flow of blood from atria to ventricles and out the great arteries is enforced by four valves that open and close in response to differences in blood pressure on their two sides. The atria and ventricles are separated by atrioventricular (AV) valves, which prevent backflow of blood into the atria when the ventricles contract (indicated as the tricuspid valve and mitral valve in Figure 1.1.5-1).

When the heart is relaxed, the AV valve flaps hang limply into the ventricles, which allows blood to flow from the atria, filling the ventricles. When the ventricles contract, the intraventricular pressure increases, which forces blood against the valve flaps, causing them to close. The flaps of the valves are supported by collagen cords,

the cordae tendineae, which anchor the flaps in the closed position and prevent them from being inverted upward into the atria. The aortic and pulmonary semilunar (SL) valves prevent backflow from the aorta and pulmonary artery trunk into the respective ventricles. In the case of the SL valves, when the ventricles contract, the intraventricular pressure rises above the pressure in the aorta and pulmonary arteries, which forces the cusps of the SL valves to flatten against the walls of the arteries, allowing blood to flow by. When the ventricles relax, blood starts to flow backward toward the ventricles, filling the cusps and closing the valves. There are no valves between the venae cavae and pulmonary vein and the right and left atria. When the atria contract, there is some backflow into these vessels; the amount is minimal, however, because as the atria contract they compress and collapse the venous entry points.

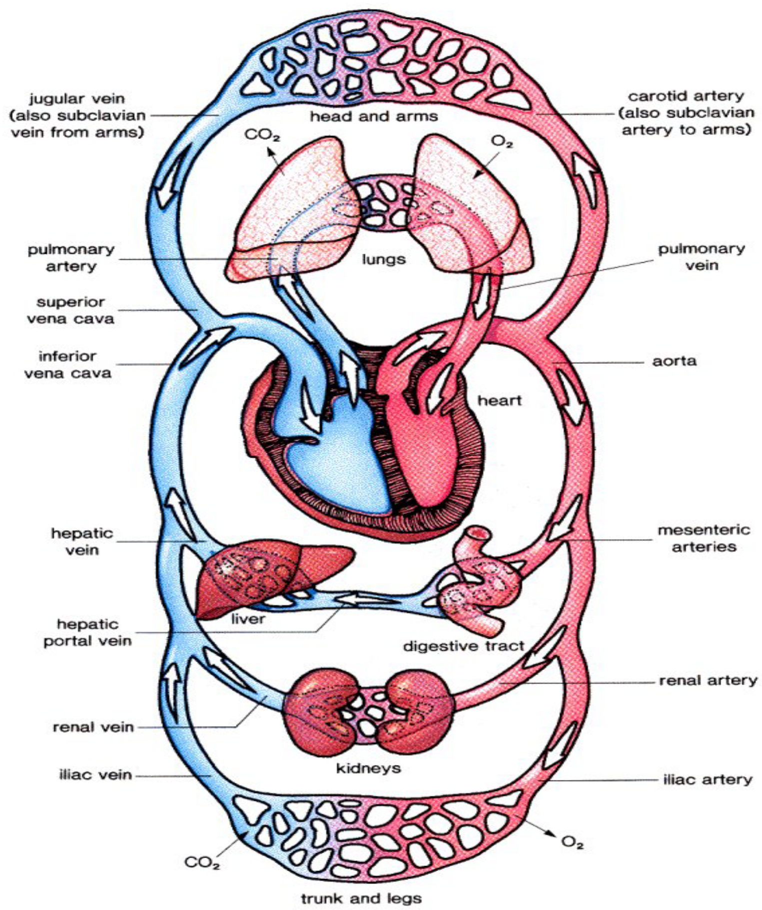

Figure 1.1.6-1. Pattern of Circulation Showing the Systemic and Pulmonary Circuits

1.1.8. Heart Sounds

When you listen to someone's heart, the typical lub-dub-pause heart sounds are caused by closing of the valves during the cardiac cycle. The first, lub sound, is caused when the AV valves close, indicating the point when ventricular pressure exceeds atrial pressure. The second, dub sound, is heard when the SL valves snap shut at the

beginning of ventricular relaxation, preventing backflow from the aorta and pulmonary artery trunk. The pause is the period between ventricular contractions when the heart is refilling with blood. Abnormal heart sounds, heart murmurs, can be indicative of valve problems. An incompetent valve, one that does not close properly, produces a swishing sound as blood backflows through the partially closed valve. A stenotic valve, one that has become stiff and does not open completely, produces a high-pitched sound or click. Like any pump, the heart can function with defective valves so long as the impairment is not too great. An incompetent valve forces the heart to pump the same blood over and over due to the backflow, while valve stenosis forces the heart to contract more forcefully to propel blood through the narrowed opening. Both problems increase the heart's workload and can be corrected through surgical repair or replacement of the defective valve.

1.1.9. The Cardiac Cycle

The <u>*cardiac cycle*</u> *includes all of the events associated with blood flow through the heart as it alternates between periods of contraction, systole, and relaxation, diastole, and is marked by a series of pressure and blood volume changes in the heart.*

If we start when the heart is relaxed, we can trace these changes through a single heart beat. During diastole, pressure in the heart is low; the SL valves are closed, preventing backflow from the aorta and pulmonary arteries, and blood flows passively through the atria and open AV valves into the ventricles (Fig. 1.1.9-1). About 80% of ventricular filling occurs during this phase. At this point the atria contract, i.e., atrial systole, compressing the blood in their chambers, increasing atrial pressure, and propelling blood out of the atria into the ventricles. This injection of blood from the atria accounts for the remaining 20% of ventricular filling and brings the ventricles to the maximum volume of blood they will contain during the cycle known as the end diastolic volume. After priming the ventricles, the atria relax and the ventricles begin to contract. Pressure in the ventricles rises sharply, closing the AV valves. For a split second the ventricles are completely closed chambers with both the AV and SL valves shut tight. This is known as the isovolumetric contraction phase. Once pressure in the ventricles exceeds the pressure in the aorta and pulmonary artery trunk, the SL valves open and blood is expelled from the ventricles in the ventricular ejection phase. At the end of ventricular contraction, a small quantity of blood remains in the ventricles and is referred to as the "end systolic volume." As the ventricles relax, intraventricular pressure drops rapidly and blood backflows from the great arteries toward the heart, closing the SL valves. During ventricular systole, the atria have been in diastole, filling with blood, and atrial pressure has been rising. Once

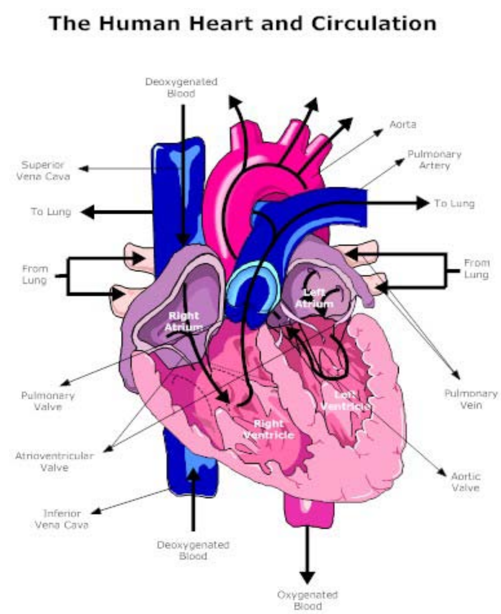

Figure 1.1.9-1. Pattern of Blood Flow Through the Heart

atrial pressure exceeds ventricular pressure, the AV valves open and the ventricles begin to refill, completing the cycle. With a heart rate of 75 beats/min, the cardiac cycle is about 0.8 s long, with atrial systole lasting 0.1 s, ventricular systole 0.3 s, and all chambers relaxed during the remaining 0.4 s. It is important to note that blood flow through the heart is controlled entirely by pressure changes and that blood flows down a pressure gradient through any available opening. The pressure changes reflect the alternating contraction and relaxation of the heart muscle and cause the heart valves to open and close, which keeps blood flowing in the proper direction. The right and left sides of the heart display a synchronous pattern of systole and diastole during the cardiac cycle. Both sides eject the same volume of blood with each heart beat, but the right side of the heart operates at a lower pressure than the left. Typical pulmonary artery systolic and diastolic pressures are 24 and 8 mmHg compared to aortic pressures of 120 and 80 mmHg.

1.1.10. Cardiac Output

Cardiac output (CO) is the volume of blood pumped by each ventricle in 1 min. It is the product of heart rate (HR) and stroke volume (SV), where SV is the volume of blood ejected by each ventricle with each contraction. Using normal resting values, average adult cardiac output can be calculated as:

$$
\begin{aligned}
\text{CO} &= \text{HR} \times \text{SV} \\
&= 75 \text{ beats/min} \times 70 \text{ mL/beat} \\
&= 5250 \text{ mL/min} \\
&= 5.25 \text{ L/min}
\end{aligned}
$$

Normal adult blood volume is about 5 L; therefore, the entire blood volume passes through both circuits of the cardiovascular system each minute when at rest. Because cardiac output is directly proportional to HR and SV, an increase in either the number of beats per minute or the amount of blood ejected with each beat will increase CO. CO is highly variable and responsive to demands such as exercise and exposure to altitude. The difference between resting and maximal CO is called the cardiac reserve. In nonathletes, cardiac reserve is typically four to five times resting CO (20-25 L/min), but elite athletes may reach cardiac outputs of 35 L/min.

1.1.11. Stroke Volume

Stroke volume is the difference between end diastolic volume (EDV) and end systolic volume (ESV). At rest normal EDV is 110-120 mL (Guyton and Hall, 2000, p. 101). At the end of ventricular contraction, there is normally 40-50 mL of blood remaining in the ventricle, giving a stroke volume of 70 mL. The fraction of the EDV that is ejected into the vasculature is called the ejection fraction, normally about 60%. Three primary factors influence these values: preload, which affects EDV, and contractility and after-load, which affect ESV (Marieb & Hoehn, 2007, p. 700). Preload (the tension on the heart muscle (Guyton & Hall, 2000, p. 103) or the degree of stretching of the muscle cells just before contraction) is the most critical factor determining stroke volume (Marieb & Hoehn, 2007, p. 700). Cardiac muscle displays a length-tension relationship, so stretching of the cardiac muscle results in an increase in contractile force. As venous return (the amount of blood returning to the heart)

increases (such as during exercise), the EDV and end diastolic pressure increase, stretching the heart muscle. As a result, contractile force is increased and allows the heart to eject a greater volume of blood into the arteries, thereby increasing SV. This ability of the heart to adapt to changing volumes of inflowing blood is called the Frank-Starling mechanism (Guyton & Hall, 2000, p. 104). Within physiological limits it allows the heart to pump all of the blood that comes to it. It also balances the cardiac output of the right and left sides of the heart. Because the pulmonary and systemic circuits are in series, if one side of the heart begins to pump more blood than the other, the increased venous return to the opposite side forces it to increase its SV and maintain an equal CO (Marieb & Hoehn, 2007, p. 701).

Contractility is the contractile force generated by the heart muscle at a given muscle cell length and is independent of muscle stretch and EDV (Marieb & Hoehn, 2007, p. 701). An increase in contractility results in ejection of more blood from the ventricles, increasing ejection fraction and SV by decreasing ESV to as little as 10-20 mL. Contractility of the heart muscle is increased by sympathetic nervous system stimulation, increased extracellular Ca^{++}, and hormones such as glucagon, thyroxin, and epinephrine. It is decreased by acidosis, elevated extracellular K^{+}, and calcium channel blocker drugs. By increasing EDV through increased venous return, and decreasing ESV through increased contractility, SV can be as much as doubled (Guyton & Hall, 2000, p. 101).

Finally, after-load, the load the heart muscle must contract against, essentially the pressure in the artery leading away from the ventricle, is not a major determinant of SV in healthy individuals (Marieb & Hoehn, 2007, p. 702). However, hypertension reduces the ability of the ventricles to eject blood into the arteries, increasing ESV and lowering SV. Left ventricular CO is not significantly affected until mean aortic pressure exceeds 160 mmHg (Guyton & Hall, 2000, p. 104).

1.1.12. Heart Rate

Heart rate is the other factor determining CO. The basic rhythmic contraction of the heart is established by an internal electrogenic system that generates rhythmical impulses to cause rhythmical contraction of the heart muscle (Guyton & Hall, 2000, p. 107). Some cardiac fibers are self-excitatory, producing automatic rhythmical action potentials. The portion of this system that displays the greatest self-excitation is the fibers of the sinus node (also known as the sinoatrial or S-A node) located in the wall of the right atrium. The sinus node generates impulses about 75 times per minute. Because this rate is faster than any other part of the internal electrogenic system of the myocardium, the sinus node sets the pace or sinus rhythm for the heart as a whole (Marieb & Hoehn, 2007, p. 693). Sinus rhythm varies with age, gender, physical fitness, and body temperature. In addition, several factors influence HR including hormone levels and extracellular ion balance, but the most important is autonomic neural input. Sympathetic stimulation increases HR and contractility, while parasympathetic stimulation decreases HR and has a small inhibitory effect on contractility. The heart receives continuous tonic inputs from both the sympathetic and parasympathetic systems, and it is the relative strength and balance of inputs that determine if sinus rhythm is increased or decreased. Strong sympathetic stimulation can increase HR and contractility enough to increase CO two- to threefold, while strong parasympathetic stimulation can actually stop the heart for several seconds then keep the HR depressed to about 40% of normal (Guyton & Hall, 2000, p. 105).

Exercise increases HR primarily through sympathetic neural stimulation; however, an abnormally fast HR (over 100 beats/min), known as tachycardia, can be caused by high body temperature, stress, drugs, or heart disease (Marieb & Hoehn, 2007, p. 704). Bradycardia, or an HR below 60 beats/min, can be caused by low body temperature, drugs, or parasympathetic neural stimulation; however, it is also a desirable consequence of endurance training. Cardiovascular conditioning causes hypertrophy of the heart, which increases SV, allowing resting HR to be lower and still provide sufficient CO. It is not uncommon for well-conditioned athletes to have a resting HR as low as 40 beats/min.

1.1.13. The Vasculature

The blood vessels form a closed system that begins and ends at the heart, together composing the vasculature. Arteries conduct blood away from the heart, while veins return blood toward the heart. The arterial and venous sides of the circulation are connected by capillaries, where exchange of fluids, nutrients, gases, hormones, ions, and other substances occurs between the blood and the interstitial fluid (Guyton & Hall, 2000, p. 144). The walls of all blood vessels, except for capillaries and the smallest arterioles, have three distinct layers (Marieb & Hoehn, 2007, p. 714). The inner blood-conducting lumen of the vessel is lined by the endothelium, a layer of flat, closely fitting cells that provide a smooth inner surface to the vessel. Outside of the endothelium is a layer of smooth muscle and elastin. Contraction of the smooth muscle results in a reduction in lumen diameter (vasoconstriction), while relaxation allows expansion of the lumen (vasodilation). Small changes in lumen diameter have a large effect on blood flow. As a result, they are critical to blood distribution and regulation of blood pressure and are influenced by sympathetic neural regulation, hormones, and local tissue conditions. Elastin is a protein that can stretch and recoil, giving the vessel elastic properties. The relative abundance of these components primarily determines the characteristics of the vessel. The outer layer of the vessel wall is composed largely of collagen fibers that protect and anchor the vessel to surrounding structures.

1.1.14. Arteries

Large arteries, such as the aorta and its major branches, are thick walled with high elastin content and relatively little smooth muscle (Marieb & Hoehn, 2007, p. 716). They receive blood from the heart at high pressure, but their large diameters make them low-resistance vessels. The high elastin content allows these vessels to serve as pressure reservoirs. When the ventricle ejects blood into the aorta, it stretches then recoils while the heart refills. This smoothes both the pressure pulse and blood flow. As the aorta stretches, it dampens the ejection pressure and then maintains blood flow as it recoils during systole. Downstream the elastic arteries branch into smaller, more muscular distributing arteries. These have relatively more smooth muscle and less elastin and are therefore more active in vasoconstriction. Arterioles, the smallest arteries, have primarily smooth muscle in their middle layer with few elastin fibers. The very smallest arterioles immediately adjacent to the capillaries may be little more than a single layer of smooth muscle cells wrapped around the endothelium. Vasoconstriction and dilation of the arterioles control blood flow into individual capillary beds and, therefore, perfusion of specific tissues.

1.1.15. Capillaries

Capillaries are the smallest blood vessels, with an average length of 0.3-1 mm and diameter of 8-10 µm, just large enough for RBCs to pass through single file (Guyton & Hall, 2000, p. 145; Marieb & Hoehn, 2007, p. 720). Capillaries are constructed of a single endothelial layer that has intercellular clefts or pores that allow movement of fluid and small molecules across the capillary wall. In the brain, these pores are absent, the endothelial cells forming continuous tight junctions; this is the structural basis of the blood brain barrier. Lipid soluble molecules, such as oxygen and carbon dioxide, can diffuse directly through the endothelial membranes without having to go through the pores, providing a much larger surface area for exchange of these molecules than for ions and other molecules that must pass through the openings between cells. Blood pressure within the capillaries tends to force water and dissolved substances out of the capillary into the interstitial space. Colloidal osmotic pressure, due to blood cells and plasma proteins that are too large to pass through the pores, causes osmotic fluid movement back into the capillary. The balance between these forces usually prevents excessive loss of fluid from the blood; however, a small net movement of fluid into the interstitium is normally observed, with the fluid being returned to the circulation via the lymphatic system. If capillary pressure increases, as, for example, due to gravitational hydrostatic pressure as discussed below, the balance can be disrupted with rapid loss of fluid from the blood and formation of tissue edema (Guyton & Hall, 2000, p. 170).

Capillaries tend to form interconnected networks of 10-100 capillaries called capillary beds. Blood flow through the capillary bed is called the microcirculation and is regulated by vasoconstriction of the terminal arteriole and a bundle of smooth muscle fibers at the root of each capillary called the precapillary sphincter. When the precapillary sphincters are relaxed, blood flows through the capillaries and exchange occurs between the blood and the tissue cells. When the sphincters are constricted, blood bypasses the tissue cells. Blood flow through any particular capillary bed is intermittent and is regulated by various hormones, including vasoconstrictors, such as norepinephrine, angiotensin, and vasopressin, and vasodilators, including bradykinin and histamine, as well as local tissue chemical conditions, including the concentrations of oxygen, carbon dioxide, and adenosine. In this way blood flow is closely matched to the metabolic demands of the tissue (Guyton & Hall, 2000, p. 175). Under conditions of hypoxemia, reduced oxygen content of arterial blood, whether due to altitude exposure, pneumonia, anemia, or carbon monoxide poisoning, is marked by an increase in tissue blood flow in an effort to maintain normal tissue oxygen levels and make up for the decreased amount of oxygen in the blood.

1.1.16. Veins

The capillaries empty into venules. The smallest venules are structurally little more than large capillaries and are very leaky. Fluids and white blood cells freely move across their walls. As the venules merge and become larger, their walls acquire smooth muscle and collagen layers and become less porous. Venules continue to converge, eventually forming veins with all three layers of typical blood vessels. Veins of any given size have thinner walls with less smooth muscle and elastin and larger lumens than arteries of comparable diameter. The veins have a large potential volume, though they are normally only partially filled, and are called capacitance vessels,

serving as blood reservoirs. Normally more than 60% of all the blood in the circulatory system is in the veins (Guyton & Hall, 2000, p. 160). If blood is lost from the body, sympathetic stimulation of the veins causes venous vasoconstriction, which reduces venous reservoir volume, making up for up to a 20% loss of total blood volume.

The large lumen of veins offers little resistance to blood flow, facilitating the movement of blood back toward the heart in the low-pressure venous circulation. Another adaptation that facilitates unidirectional flow toward the heart in this low-pressure circuit is venous valves that prevent backflow of blood. Venous valves are formed from folds of the endothelial layer and are similar in structure to the semilunar valves of the heart. Valves are most prominent in the veins of the limbs where blood must flow upward against the pull of gravity. You can demonstrate the effect of these valves by collapsing a vein on the back of your hand or in your wrist. Let your hand hang down so the veins become engorged with blood. Place a finger across a vein on the back of your hand or on the inside of your wrist, then run another finger or your thumb up the vein toward your heart. The vein will stay collapsed until you remove your finger because the valves prevent blood from flowing backward into the collapsed vein.

1.1.17. Blood Flow

Blood flow through any part of the circulation is described by Ohm's Law (Guyton & Hall, 2000, p. 146):

$$Q = \Delta P/R$$

where Q is blood flow, ΔP is the pressure difference from one end of a vessel to the other, and R is the resistance. Blood flow is simply the volume of blood flowing through a vessel, tissue, organ, or the entire circulation in a given time (mL/min). For the entire circulation, flow is equivalent to cardiac output. Blood pressure is the force exerted by the blood against the walls of the vessel and is usually expressed in mmHg. It is the difference in blood pressure, the pressure gradient from one end of the vessel to the other, that provides the driving force for blood flow. Resistance is the impediment to blood flow. It cannot be measured directly but is estimated by measuring the blood flow and pressure difference between two points in a vessel. Vascular resistance is often expressed in peripheral resistance units (1 PRU = a flow of 1 mL/s with a 1-mmHg pressure gradient). The total resistance of the systemic circulation is about 1 PRU. Because the pulmonary circuit operates at a lower pressure but has the same flow as the systemic circuit, its total resistance is calculated to be about 0.14 PRU. Conductance, the blood flow through a vessel for a given pressure difference, is the reciprocal of resistance. Slight changes in a vessel's diameter have a large effect on its conductance. This is due to the fact that in accordance with Poiseuille's Law, conductance is proportional to the fourth power of the diameter of the vessel (Guyton & Hall, 2000, p. 150). Therefore, a fourfold increase in the diameter of a vessel decreases resistance and increases flow through the vessel 256-fold if ΔP is maintained.

Systemic arterial blood pressure is pulsatile due to the rhythmic ejection of blood into the aorta by the left ventricle. Systolic pressure, the peak pressure achieved during ventricular contraction, is about 120 mmHg at the level of the heart in healthy adults (Marieb & Hoehn, 2007, p. 724). Diastolic pressure, the lowest pressure

reached during ventricular relaxation, is about 80 mmHg. The difference between systolic and diastolic pressures is called the pulse pressure. Mean arterial pressure (MAP), the average pressure in the vessel throughout the cardiac cycle and the driving force that propels blood through the vasculature, is about 100 mmHg. Both MAP and pulse pressure decrease with increasing distance from the heart. The greatest drop in MAP and pulse pressure occurs in the arterioles, so that by the time blood reaches the terminal arterioles, MAP is about 35 mmHg and blood flow is steady with pulse pressure equal to zero. This is due to the high resistance of the small-diameter arterioles and their inelasticity. Pressure at the arterial end of a systemic capillary is about 35 mmHg but drops to 10-15 mmHg at the venous end, with an average functional pressure across the capillary bed of about 17 mmHg (Guyton & Hall, 2000, p. 145). Low capillary pressures are essential due to their fragile structure and porous nature.

Blood pressure in the venous circulation is nonpulsatile, and the pressure gradient between the venules that receive blood from the capillary beds (10-15 mmHg) and the vena cava where it empties into the right atrium, called central venous pressure (0 mmHg), is too small to propel blood back to the heart despite the low resistance to flow in veins and valves to prevent backflow. Three systems help facilitate venous return (Marieb & Hoehn, 2007, p. 726). The respiratory pump is due to pressure changes during ventilation. When we inhale, pressure in the abdomen increases, squeezing veins within the abdomen and propelling blood toward the heart. During exhalation, abdominal pressure decreases, allowing the veins to expand and refill with blood. Chest pressure follows an opposite pattern, decreasing during inhalation, allowing thoracic veins to expand, and increasing during exhalation. The muscular pump results from contraction and relaxation of skeletal muscles surrounding deep veins of the limbs. As the muscles contract, they compress the veins, propelling blood toward the heart. The final mechanism is contraction of smooth muscle in the walls of the veins in response to sympathetic neural stimulation.

The pressures described above are referenced to the level of the heart and are a close approximation throughout the body for an individual who is lying down. But in an upright person, gravity has a large effect on blood pressure throughout the vasculature. Gravitational or hydrostatic pressure occurs in the vascular system due to the weight of the blood (Guyton & Hall, 2000, p. 157). In the upright person, pressures at the level of the heart remain as described above with MAP equal to 100 mmHg and right atrial pressure equal to 0, but the addition of hydrostatic pressure causes MAP in the feet to rise to about 190 mmHg and venous pressure to 90. Pressures at other levels of the body below the heart lie proportionately between these extremes, and pressures in regions above the heart will be proportionately decreased. For example, venous pressure in the hand rises to about 35 mmHg, while pressure in the veins of the neck drops to zero, at which time they are collapsed by atmospheric pressure. Collapse prevents creation of negative pressure in the veins of the neck, but within the skull, which forms a noncollapsible chamber, negative pressures can exist within the dural sinuses. High venous pressures in the lower extremities make functioning of the venous valves and muscular pump very important. The efficiency of these adaptations allows the venous pressure in the feet of a walking adult to remain below 25 mmHg, but in their absence, that is for an individual standing still, venous pressure rises to 90 mmHg within 30 s. As venous pressure rises, capillary pressure also rises, and transduction of fluid out of the capillaries into the tissues increases. This movement of fluid out of the vasculature causes the legs to swell and blood volume to decrease.

Indeed, 10%-20% of blood volume can be lost from the circulation during 15 min of standing at attention. These hydrostatic effects are exaggerated in hyper-G environments and essentially disappear in the microgravity of space flight.

Arterial blood pressure is closely and rapidly regulated. Pressure varies directly with CO, vascular resistance, and blood volume (Marieb & Hoehn, 2007, p. 726). A change in any of these variables is quickly compensated by the others to maintain pressure homeostasis. For example, if blood pressure should start to fall due to hemorrhage, baroreceptors (pressure receptors) in the carotid sinuses of the internal carotid arteries, which provide the major blood supply to the brain, and in the aortic arch detect the pressure drop, sending signals to the central nervous system (CNS), stimulating increased sympathetic and decreased parasympathetic neural output. Sympathetic stimulation causes systemwide vasoconstriction, increasing arteriolar resistance. This increased resistance elevates arterial pressure but also decreases downstream capillary pressure, allowing a net flow of fluid into the capillaries from the interstitial fluid and adding to blood volume (Rainford & Gradwell, 2006, p. 19). Venous vasoconstriction moves blood out of the venous reservoir, increasing CO. Sympathetic nervous stimulation also increases both heart rate and contractility, increasing stroke volume and further increasing CO. All of these responses work together to maintain MAP in the face of decreased blood volume (Guyton & Hall, 2000, p. 187). In the face of elevated blood pressure, an opposite response is seen, with an inhibition of sympathetic and stimulation of parasympathetic neural output, resulting in generalized vasodilation with decreased resistance, a shifting of blood into the venous reservoir, and a decrease in heart rate and contractility, all contributing to a lowering of MAP. Neural regulation of blood pressure is very rapid and compensates for the changes that occur during daily activities. For example, when you stand up after lounging on the couch, blood pressure above your heart drops rapidly. The pressure drop is detected by the carotid baroreceptors, stimulating a strong sympathetic discharge that minimizes the decrease in blood pressure and preserves brain perfusion. Longer term regulation of blood pressure is mediated through hormones that control blood volume via the kidneys. This close regulation of blood pressure during a wide variety of physiological and psychological stressors helps to ensure perfusion of body tissues.

1.1.18. Summary

This chapter attempts to select and summarize key concepts of cardiovascular physiology from three respected physiology texts that are of particular importance and interest to the aerospace physiologist. For further study of fundamental cardiovascular physiology, I refer you to either Guyton & Hall (2000) or Marieb & Hoehn (2007) for a detailed treatment of any of the topics touched on in this chapter and many more. For a detailed examination of the cardiovascular consequences of the stressors associated with the aerospace environment, including exercise, hypoxia, anti-G straining maneuver, and positive pressure breathing, I refer you to Rainford & Gradwell (2006).

References
Guyton AC, Hall JE: Textbook of Medical Physiology, 3rd ed. Philadelphia: W.B. Saunders Company, 2000.
Marieb EN, Hoehn K: Human Anatomy and Physiology, 7th ed. San Francisco: Pearson Benjamin Cummings, 2007.
Rainford DJ, Gradwell DP: Ernsting's Aviation Medicine, 4th ed. London: Hodder Arnold, 2006.

Concepts

Cardiac cycle, phases and functions
Heart valves, function
Heart, structure and function
Hemoglobin, structure and function
Transport vehicle of the cardiovascular system

Vocabulary

Arterial and venous
Arteries
Atria and ventricles
Blood pressure
Capillaries
Cardiac cycle
Cardiac output
Heart rate
Hemoglobin
mmHg
Plasma
Pulmonary circulation
Red blood cells, erythrocytes
Systemic circulation
Systolic and diastolic
Veins

1.2. Respiration

Col Paul W. Fisher, USAF, BSC

1.2.1. Function

> *The* <u>*primary function of the respiratory system*</u> *is the uptake of oxygen (O_2) and the removal of carbon dioxide (CO_2). Oxygen serves as the terminal electron acceptor at the end of the electron transport chain in the mitochondria and as such is essential to aerobic energy production, which accounts for more than 95% of the body's energy expenditure (Guyton & Hall, 2000).*

Once oxygen picks up two electrons it combines with two H+ ions, forming water. This metabolic water can account for up to 10% of the body's daily water requirement. Carbon dioxide is produced during the breakdown of nutrients (carbohydrates, proteins, and lipids) in the citric acid or Krebs cycle. This CO_2, produced in the mitochondria, diffuses out of the cells into the blood and is ultimately expired through the lungs (Guyton & Hall, 2000). The rate of O_2 consumption and CO_2 production are closely tied to and regulated by the energy requirements of the cells, tissues, organs, and ultimately the entire body.

The process of providing oxygen to the cells for energy production and removal of carbon dioxide can be divided into a series of functional events:

- <u>Pulmonary ventilation</u>, the movement of air into and out of the lungs
- Diffusion of O_2 and CO_2 between the lungs and the blood, sometimes called external respiration
- Transport of the respiratory gases between the lungs and the tissues, a function of the cardiovascular system with blood as the transport medium
- Movement of gases between the blood, the interstitial fluid, and the cells, sometimes called internal respiration
- The utilization of O_2 and production of CO_2 in the cell, known as <u>cellular respiration</u> (Marieb & Hoehn, 2007)

Only the first two events are a special function of the respiratory system, but if the cells are to be provided with O_2 and have their CO_2 waste product removed, the respiratory and circulatory systems must work together and be closely regulated.

1.2.2. Anatomy of the Respiratory System

Air enters the conducting passages of the respiratory system via the mouth and nose. The nose does a particularly good job of conditioning the inspired air. The hairs of the nose remove large particles, while conchae, vane-like projections within the nasal passages, are important to filtration of smaller particles through a process known as turbulent precipitation. As air flows through the convoluted passageways created by the conchae, it is forced to repeatedly change direction. The momentum of heavier particles, such as dust, pollen, and bacteria, causes them to impact the conchae and become entrapped in mucus coating the walls. Turbulent precipitation is so effective that virtually no particles larger than 6 µm that enter the nose make it to the lungs (Guyton & Hall, 2000). Ciliated cells of the mucosa lining the nasal passages sweep

the contaminated mucus toward the throat where it is swallowed or coughed and expelled. In addition to cleansing the air, the large, highly vascularized surface area of the nasal passages also warms and humidifies the inspired air to within 1° F of body temperature and to 97%-98% saturation with water vapor. The paranasal sinuses in the frontal, sphenoid, ethmoid, and maxillary bones lighten the skull and contribute to warming and humidifying inspired air (Marieb & Hoehn, 2007). If the nasal mucosa becomes infected by viruses or bacteria, or is irritated by allergens, the mucosa can become inflamed with excessive production of mucus. Because the nasal mucosa is continuous with the rest of the respiratory tract, infection often progresses from nose to throat to chest. Spread of infection into the paranasal sinuses can result in sinusitis, with mucus blocking the passages connecting the sinuses to the nasal cavity, resulting in sinus headaches and difficulty in equalizing pressure between the sinuses and the ambient environment during altitude changes.

The nasal and oral cavities merge at the throat or pharynx (Marieb & Hoehn, 2007). The pharynx serves as a passageway for both air and swallowed food. The eustachian tubes (also known as the pharyngotympanic or auditory tubes), which allow pressure to equalize between the middle ear and the atmosphere, open into the upper or nasopharynx. The tubal tonsil arches over the opening of the eustachian tube and helps prevent the spread of infection from the nasopharynx into the middle ear. The pharynx extends for about 13 cm to the larynx or voice box, which is visible externally as the Adam's apple. The larynx is responsible for routing air and food into the proper channels. When only air is flowing through the larynx, the inlet to the larynx is open and the epiglottis, a cartilage projection at the top of the larynx, is oriented upward. During swallowing, the larynx is pulled upward and the epiglottis tips to cover the laryngeal opening, directing food into the esophagus and preventing it from entering the lower respiratory passages. If anything other than air enters the larynx, a strong cough reflex is stimulated, expelling the substance. The larynx also contains the vocal chords and is involved in voice production. The true vocal chords, or vocal folds, and the opening between them through which air passes, are called the glottis. The glottis can act as a sphincter, preventing air passage. During the anti-G straining maneuver (AGSM), the glottis is closed to prevent exhalation while abdominal and thoracic muscles contract, increasing intrathoracic pressure.

The trachea, or windpipe, descends from the larynx until it divides into the two main bronchi at mid-chest level (Fig. 1.2.2-1). The trachea is quite flexible but has C-shaped rings of cartilage that keep it from collapsing during the pressure changes associated with breathing. The main bronchi extend to the lung on their respective sides. Once inside the lung the bronchi divide into lobar or secondary bronchi, two on the left and three on the right, each supplying one lung lobe. The lobar bronchi then undergo repeated branching for up to 23 generations. Branches less than 1 mm in diameter are called bronchioles, with the smallest terminal bronchioles being less than 0.5 mm in diameter. This repeated branching pattern of the conducting respiratory pathways is called the bronchial or respiratory tree (Marieb & Hoehn, 2007). Ciliated and mucus producing cells are found in the lining of the larger bronchi but are absent in the bronchioles. Ciliated cells in the bronchi, trachea, and larynx sweep mucus upward toward the pharynx, where it is swallowed. Contaminants that reach the bronchioles are removed primarily by macrophages, a type of white blood cell. As successive branches become smaller, the amount of cartilage in the walls of the respiratory tree decreases and the amount of smooth muscle increases. The bronchioles completely

lack cartilage support and have a complete layer of smooth muscle, which can alter their diameter.

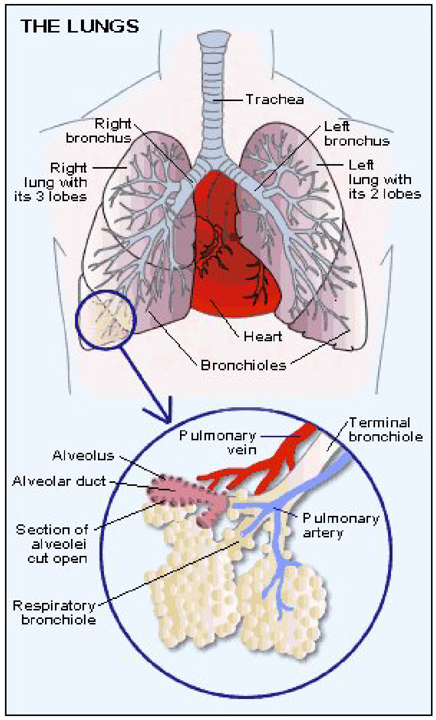

Figure 1.2.2-1. Respiratory System Anatomy

All of the structures described above are referred to as conducting zone structures, as they function to conduct air to and from the site of gas exchange. Respiratory zone structures are characterized by the presence of gas-filled sacks called alveoli, the actual site of gas exchange within the lungs (Marieb & Hoehn, 2007). The respiratory zone structures include respiratory bronchioles, the smallest bronchioles that have scattered alveoli protruding from them; alveolar ducts, winding passages with out-pocketing alveoli that lead to terminal clusters of alveoli, which resemble a bunch of grapes; and the alveoli themselves (Fig. 1.2.2-2). Alveoli are composed of a single layer of epithelial cells surrounded by a thin basement membrane. Each is covered by a meshwork of pulmonary capillaries, creating a respiratory membrane with gas on one side and blood flowing past on the other. There are over 300 million alveoli in the lungs. They make up most of the lung volume and provide a tremendous surface area for gas exchange. It is estimated that the total surface area of the respiratory membrane is 70 m^2, the area of a 25- x 30-ft room.

The lungs occupy almost the entire chest cavity, extending from the collar bones to the diaphragm, with the front, side, and back surfaces in close contact with the ribs. The lungs are slightly different sizes and shapes to accommodate the heart, with the left lung being the smaller. The pulmonary blood vessels enter and exit the lungs at the hilum, where the main bronchi also enter. Each lung is enclosed by a thin membrane called the visceral pleura. A second membrane, the parietal pleura, lines the inner surface of the chest wall and the top of the diaphragm and extends between the lungs and around the heart. The space between the membranes, the pleural cavity, is filled with pleural fluid, which is secreted by the membranes. The fluid provides lubrication so the lungs can glide easily over the chest wall and creates surface tension, which

prevents the pleural membranes from separating, forcing the lungs to expand and contract with movements of the chest wall during breathing.

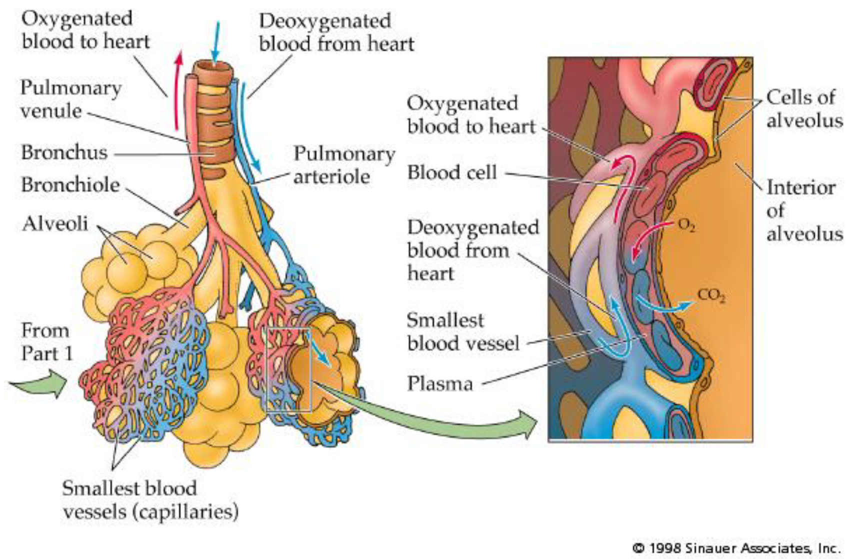

Figure 1.2.2-2. Respiratory Zone Structures

1.2.3. Ventilation of the Lungs

When the glottis is open and there is no air moving into or out of the lungs, the pressure throughout the respiratory tree, including the alveoli, is equal to atmospheric pressure (Guyton & Hall, 2000). This is considered the zero reference pressure of the airways. During inspiration, the inspiratory muscles contract, expanding the volume of the thoracic cavity. The diaphragm contracts, pulling the lungs downward and lengthening the thoracic cavity (Fig. 1.2.3-1).

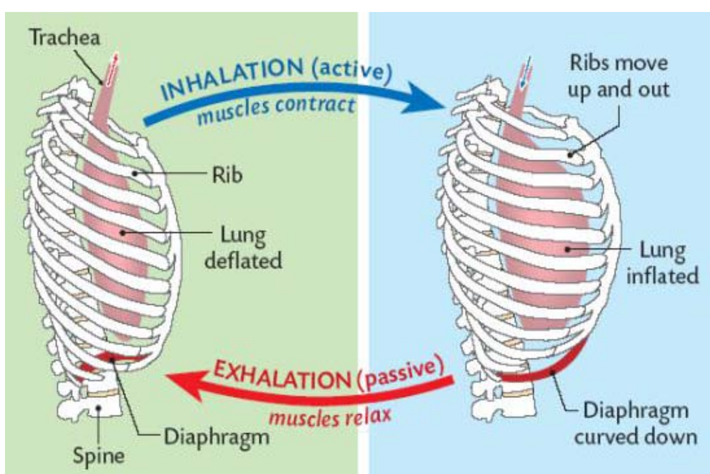

Figure 1.2.3-1. Breathing Movements (the Respiratory Muscles Contract During Inhalation and Relax During Exhalation)

The external <u>intercostal muscles</u> between the ribs contract, pulling the ribs upward and outward, increasing the diameter of the chest. In accordance with Boyle's Law, as the volume of the chest increases the intra-thoracic pressure decreases, creating a slight negative pressure in the alveoli of approximately -1 cm H_2O. This

pressure difference is sufficient to pull 0.5 L of air into the lungs during the 2 s of normal quiet inspiration. During forced inspiration, in response to exercise, obstructive lung disease, or resistance from oxygen equipment, the diaphragm and external intercostal muscles contract more vigorously and accessory muscles that aid in expansion of the rib cage are recruited, resulting in greater expansion of the thoracic cavity and creation of a greater negative plural pressure, resulting in an increased rate of flow and volume of air entering the lungs.

Expiration during quiet breathing is a passive process due to the elastic recoil of the lungs and chest cage structures. As the inspiratory muscles relax, the rib cage descends and the diaphragm recoils upward, decreasing the volume of the thoracic cavity and increasing the plural pressure to approximately +1 cm H_2O. This increased pressure forces 0.5 L of air out of the lungs during the 2 to 3 s of normal expiration. Under resting conditions the respiratory muscles only perform work during inspiration and relax during expiration. On the other hand, forced expiration is achieved by contraction of the internal intercostal muscles, which depress the rib cage, and the oblique and transverse abdominal muscles, which compress the abdominal cavity, forcing the abdominal organs upward against the diaphragm, reducing thoracic volume and generating elevated intra-thoracic pressures. This allows rapid and forceful expulsion of air from the lungs during exercise, against the resistance of oxygen equipment, and during positive pressure breathing. During quiet breathing, 3% to 5% of the body's total energy expenditure is dedicated to pulmonary ventilation, but during heavy exercise or if breathing resistance is increased, the amount of energy required to ventilate the lungs can increase 50-fold and can become a limiting factor in exercise intensity (Guyton & Hall, 2000).

Replenishing the air in the alveoli where gas exchange can occur between the lungs and the blood is the ultimate purpose of pulmonary ventilation; however, because of the in and out reciprocal pattern of ventilation, not all of the tidal volume contributes to alveolar ventilation. The last air inhaled during inspiration is the first air exhaled during the subsequent exhalation. This approximately 150 mL of last air in/first air out fills the conducting passageways where no gas exchange occurs. This volume is known as the anatomical dead space. Alveolar ventilation rate (AVR) can be calculated as:

$$AVR = Freq\ (VT - VD) \text{ where}$$

Freq = ventilation frequency (breaths/min)
VT = tidal volume (mL/breath)
VD = dead space volume (mL/breath)

For an average adult male breathing quietly:

$$AVR = 12 \times (500 - 150) = 4200 \text{ mL/min}$$

Because anatomical dead space is constant for any given individual, increasing VT by breathing more deeply is more effective in increasing AVR than increasing Freq; in fact, AVR drops rapidly with rapid shallow breathing because a greater percentage of VT remains in the dead space (Marieb & Hoehn, 2007). Oxygen masks increase functional dead space and reduce AVR, forcing the aircrew member to increase the depth or frequency of breathing to maintain alveolar ventilation. As a result, minimizing

dead space volume is an important consideration in oxygen equipment design (Rainford & Gradwell, 2006).

1.2.4. Alveolar Gas Tensions

The partial pressures of gases in the alveoli are significantly different from those of atmospheric air. Oxygen is continually absorbed from the alveoli into the blood, while at the same time it is constantly being replenished by alveolar ventilation (Guyton & Hall, 2000). Increased oxygen consumption, for example during exercise, reduces alveolar oxygen pressure (PAO_2); conversely, increased alveolar ventilation elevates it. Moderate exercise increases oxygen absorption from the alveoli from 250 to 1000 mL/min, requiring a fourfold increase in ventilation to maintain normal PAO_2. On the other hand, carbon dioxide is continually being formed by the body and delivered to the lungs for elimination. Increased CO_2 production by the tissues will elevate alveolar CO_2 partial pressure ($PACO_2$), and unlike PAO_2, alveolar CO_2 pressure ($PACO_2$) is inversely proportional to alveolar ventilation rate. Under normal resting conditions, with a whole body CO_2 production rate of about 200 mL/min and alveolar ventilation of 4200 mL/min, $PACO_2$ is 40 mmHg.

Alveolar PAO_2 can be calculated using the alveolar gas equation (Rainford & Gradwell, 2006):

$$PAO_2 = PIO_2 - PACO_2 \text{ X } (FIO_2 + [1 - FIO_2] / R) \text{ where}$$

PIO_2 = oxygen partial pressure (PO_2) of inspired tracheal gas, i.e., gas saturated with water vapor at body temperature (37° C). Water vapor pressure at 37° C is 47 mmHg and is wholly dependent on temperature and, therefore, independent of altitude.

Therefore,

$$PIO_2 = (P_B - 47) \text{ X } FIO_2 \text{ where}$$

P_B = barometric pressure

$PACO_2$ = alveolar carbon dioxide partial pressure (40 mmHg under normal conditions)

FIO_2 = fractional concentration of oxygen in the inspired gas (0.21 for atmospheric air)

R = respiratory exchange ratio (also called the respiratory quotient, RQ), which is the ratio of CO_2 produced/O_2 consumed by the tissues (Rainford & Gradwell, 2006).

R is dependent on diet because macronutrients enter the Krebs' cycle at different points, resulting in different rates of CO_2 production. Oxidation of carbohydrates results in an R = 1.0; oxidation of fats or protein gives an R = 0.7. For a typical mixed diet, an R = 0.85 can be assumed.

At sea level breathing air

$$PIO_2 = (760 - 47) \times 0.21 = 150$$

Therefore,

$$PAO_2 = 150 - 40\ (0.21 + [1 - 0.21] / 0.85) = 104 \text{ mmHg}$$

When breathing 100% oxygen, $FIO_2 = 1$, so the alveolar gas equation simplifies to:

$$PAO_2 = PIO_2 - PACO_2$$

$$= (P_B - 47) - PACO_2$$

Solving for P_B we can determine that a sea level equivalent PAO_2 of 104 mmHg can be maintained while breathing 100% oxygen at P_B = 191 mmHg, which is the pressure at approximately 33,500 ft. Similarly, if we solve the alveolar gas equation for FIO_2, we can calculate the required percentage of oxygen in the breathing gas delivered by an aircrew breathing system to maintain a desired alveolar oxygen tension at any altitude.

1.2.5. Gas Exchange in the Lung

Gas exchange occurs between the alveolar gas and the blood by simple diffusion across the respiratory membrane.

The alveoli are covered by an almost solid network of interconnecting capillaries (Guyton & Hall, 2000). The respiratory membrane between the alveolar gas and the blood consists of:

- A layer of fluid lining the inside of the alveolus
- The alveolar epithelium, made up of a single layer of thin cells
- Epithelial basement membranes of the alveoli and the capillaries, which fuse in many places
- The capillary epithelium, again made up of a single layer of cells

Despite these many layers, the respiratory membrane is very thin, averaging only 0.6 µm. The distance gases must diffuse and, therefore, the functional thickness of the respiratory membrane is also reduced by the fact that the pulmonary capillaries average only 5 µm in diameter, forcing the red blood cells to deform and squeeze through the vessels, bringing the RBC membrane in contact with the capillary walls so that gases need not diffuse through a significant layer of plasma.

The factors that determine how fast a gas will pass through a membrane are:

- The thickness of the membrane
- The surface area of the membrane
- The diffusion coefficient of the gas within the membrane
- The partial pressure difference of the gas across the membrane

The thickness of the respiratory membrane, although extremely thin, can be increased by accumulation of fluid in the space between the alveolar and capillary basement membranes or inside the alveoli themselves as a result of pneumonia or by diseases such as pulmonary fibrosis. Increasing the thickness of the membrane more than two to three times normal will significantly impair gas exchange. Surface area of the respiratory membrane can be severely decreased by diseases such as emphysema, cancer, or bronchial obstruction. The diffusion coefficient of a gas is a characteristic of the gas itself related to its solubility in the membrane, which is essentially the same as its solubility in water, and the square root of its molecular weight. The rate of diffusion of CO_2, for a given pressure difference, is 20 times greater than O_2; therefore, CO_2 moves across the respiratory membrane much faster than O_2. The partial pressure difference across the respiratory membrane is the most important factor for aerospace physiology. The difference in partial pressure of a gas between the alveoli and the pulmonary capillary blood is a measure of the net tendency of the gas molecules to move through the membrane. The net movement of gas will be from an area of high partial pressure to an area of low partial pressure. At sea level normal PAO_2 = 104 mmHg and $PACO_2$ = 40 mmHg. Oxygen pressure in mixed venous blood is typically 40 mmHg, while venous PCO_2 = 45 mmHg. Therefore, the net movement of O_2 across the respiratory membrane is from the alveolar gas to the blood, and the net movement of CO_2 is from the blood into the alveoli.

The rate of gas exchange is very rapid. At rest it takes approximately 0.75 s for blood to transit the pulmonary capillary, yet oxygen tension in the blood is essentially equal to that of the alveolar gas within 0.2-0.25 s (Rainford & Gradwell, 2006). Even under heavy exercise when the capillary transit time for a red blood cell is reduced to one-third that at rest, there is still sufficient time for oxygen tensions to equilibrate across the respiratory membrane. At altitude under hypoxic conditions, when PAO_2 is reduced, the driving force for the movement of oxygen across the respiratory membrane falls and the rate of transfer is slowed. If PAO_2 drops to 40 mmHg, there is still time for equilibration between the alveolar gas and venous blood when at rest, but even moderate exercise will result in the oxygen tension of end capillary blood being below alveolar PO_2. Therefore, exercise can exacerbate hypoxia due to the slowed rate of oxygen exchange in the lung.

Another complication of gas exchange in the lung is the ventilation/perfusion (VA/Q) ratio, that is, the balance between the ventilation of an alveolus and the blood flow through its alveolar capillaries. If the ventilation of a given alveolus is normal, and the flow of blood through the capillaries of that alveolus is also normal, VA/Q is said to be normal or equal to 1 (Guyton & Hall, 2000). If an alveolus is not ventilated but still has perfusion, then VA/Q equals zero. Under these conditions, the blood will absorb O_2 from the alveolar gas and deposit CO_2 until the alveolar gas pressures equal those of mixed venous blood: PO_2 = 40 mmHg, PCO_2 = 45 mmHg. This situation is known as shunt because once gas pressures are equal between the alveolus and the blood no gas exchange occurs and it is as if the blood did not flow through the lungs. On the other hand, if an alveolus is ventilated but not perfused, VA/Q equals infinity, no O_2 is removed from the alveolus, and no CO_2 is deposited, so the alveolar gas tensions will approach those of humidified air: PO_2 = 149 mmHg, PCO_2 = 0 mmHg. This situation effectively increases the physiologic dead space; that is, it increases the percentage of tidal volume going to parts of the lung where no gas exchange occurs. Various parts of the lung may experience degrees of VA/Q mismatch between these two extremes. One cause of VA/Q mismatch is gravity. For a healthy individual in an upright posture,

gravity causes a stretching or distension of the upper part of the lung and a compression of the lower lung, resulting in greater ventilation of the lower alveoli compared to the upper alveoli, while at the same time blood flow through portions of the lung above the heart is reduced and flow below the heart is increased. Although both ventilation and perfusion increase from the upper to the lower lung, the difference in blood flow is greater than the difference in ventilation, so VA/Q may be as high as 2.5 at the top of the lung and as low as 0.6 at the bottom of the lung. The degree of mismatch is decreased during exercise due to increased blood flow to the upper part of the lung, and the effect is eliminated in the microgravity of space but accentuated in hyper-G environments (Rainford & Gradwell, 2006).

The body has control mechanisms to reduce the inefficiency of VA/Q mismatch (Marieb & Hoehn, 2007). If PAO_2 is low due to poor ventilation, the terminal arterioles feeding the capillaries of that alveolus constrict, redirecting blood flow to better ventilated parts of the lung. If PAO_2 is high, the arterioles dilate. This response is opposite of that seen in the systemic circulation, where low tissue PO_2 results in vasodilatation. While this auto-regulatory mechanism is adaptive in reducing VA/Q mismatch, under hypoxic conditions where the PO_2 in all alveoli falls it can result in generalized pulmonary vasoconstriction, which may contribute to the pulmonary hypertension and high altitude pulmonary edema observed during chronic hypoxia. In addition to the vascular response to PO_2, the bronchioles respond to alveolar PCO_2. Increased $PACO_2$ results in bronchiolar dilation, which increases ventilation and drives PCO_2 down; conversely, low PCO_2 causes bronchiolar constriction, limiting ventilation of regions with limited perfusion. These two mechanisms serve to synchronize ventilation and perfusion, increasing efficiency of gas exchange.

1.2.6. Transport of Oxygen in the Blood

Once oxygen has diffused from the alveolar gas to the blood, it is transported in two ways: dissolved in the plasma and bound to hemoglobin in the red blood cells. Because of the low solubility of O_2 in water, a normal arterial blood PO_2 of 95 mmHg results in only about 0.29 mL of oxygen being dissolved in every 100 mL of plasma. When blood PO_2 falls to 40 mmHg in the tissue capillaries, approximately 0.12 mL of O_2 remains dissolved in the plasma. Therefore, only 0.17 mL of O_2 is delivered in the dissolved state to the tissues by each 100 mL of blood (Guyton & Hall, 2000). This accounts for less than 3% of the oxygen delivered to the tissues.

> *Over 97% of the oxygen transported by the blood is reversibly bound to the hemoglobin of the red blood cells as <u>oxyhemoglobin</u>. Each hemoglobin molecule has four subunits, each with an oxygen-binding heme group, so each hemoglobin molecule can bind four molecules of oxygen (Marieb & Hoehn, 2007).*

Once the first oxygen molecule binds a heme group, the hemoglobin molecule changes shape, facilitating the uptake of successive O_2 molecules until the hemoglobin is fully saturated with four O_2 molecules. Similarly, release of one O_2 molecule enhances the unloading of the next. Because the affinity of hemoglobin for O_2 changes with successive binding of each O_2 molecule, the relationship between hemoglobin saturation and PO_2 is not linear. This relationship is represented by the <u>oxygen-hemoglobin dissociation curve</u>, which has a characteristic sigmoid shape (Fig. 1.2.6-1).

The S-curve has a steep slope for PO_2s between 10 and 50 mmHg and then plateaus between 70 and 100 mmHg. Under normal sea level conditions, the PO_2 of arterial blood is about 95 mmHg, resulting in 97% hemoglobin saturation. The PO_2 of mixed venous blood is only 40 mmHg, just beyond the inflection point where the oxygen-hemoglobin dissociation curve becomes more steep, resulting in a hemoglobin saturation of 75%.

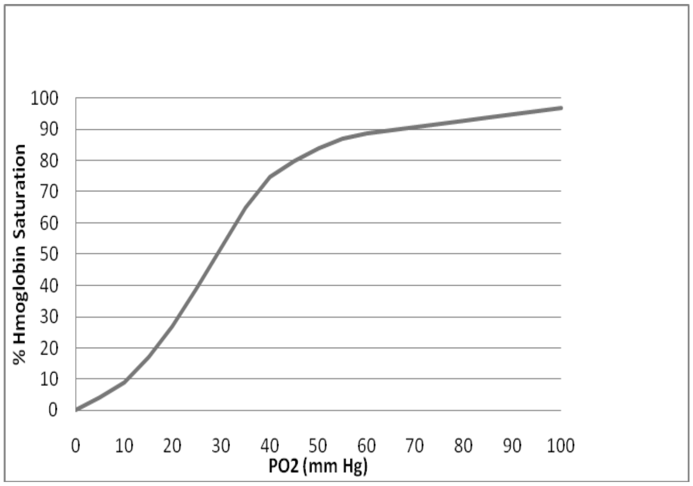

Figure 1.2.6-1. Oxygen-Hemoglobin Dissociation Curve

The amount of O_2 bound to the hemoglobin in 100 mL of arterial blood at 97% saturation is about 19.4 mL, just below the maximum of 20 mL O_2/100 mL blood (or 20 vol%) present when hemoglobin is fully saturated (Guyton & Hall, 2000). After the blood transits the tissue capillaries and blood PO_2 has fallen to 40 mmHg and hemoglobin saturation to 75%, the amount of O_2 bound to hemoglobin is about 14.4 mL. Therefore, under normal conditions about 5 mL of O_2 is released to the tissues from each 100 mL of blood that transits the tissue capillaries. The percentage of O_2 released to the tissues is called the utilization coefficient and, in this case, would be 22%. During strenuous exercise the muscles consume oxygen at a rapid rate, lowering interstitial fluid PO_2 to as little as 15 mmHg. At a PO_2 of 15 mmHg, hemoglobin saturation falls to 22%, where only 4.4 mL of O_2 remain bound to hemoglobin in each 100 mL of blood, increasing the amount of O_2 delivered to the tissues from 5 to 15 mL or three times the normal delivery rate. During heavy exercise the utilization coefficient for the entire body can increase to 75%-85%. In some tissues where blood flow is restricted or metabolic rates are extremely high, coefficients approaching 100% have been recorded.

The S-shape of the oxygen-hemoglobin dissociation curve reveals two important characteristics of oxygen transport (Guyton & Hall, 2000). In the upper flat portion of the curve, large changes in PO_2 result in little change in hemoglobin saturation, buffering the effect of mild hypoxia. For example, at an altitude of 8000 ft, PAO_2 falls to about 63 mmHg; however, hemoglobin saturation of blood leaving the pulmonary capillaries is still about 90%. In contrast, on the steep part of the curve at lower PO_2 values, small drops in PO_2 result in large changes in saturation and extraction coefficient, facilitating the rapid offloading of oxygen to the tissues. As a result, despite a significant drop in PAO_2 from 104 mmHg at sea level to 63 mmHg at 8000 ft, delivery of a normal 5 mL O_2/100 mL blood to the tissues only requires a drop in tissue PO_2

from 40 mmHg to 35 mmHg. In this way hemoglobin buffers tissue PO_2 and stabilizes O_2 delivery.

1.2.7. Factors Affecting Hemoglobin Saturation

Several factors affect hemoglobin saturation including CO_2 concentration, pH, temperature, and 2,3-diphosphoglycerate (DPG) concentration (Guyton & Hall, 2000). Each of these factors can shift the relative position of the oxygen-hemoglobin dissociation curve without changing its basic sigmoid shape. For example, in the lungs CO_2 diffuses from the blood into the alveoli, lowering blood PCO_2 and raising pH due to a decrease in blood carbonic acid. This causes an increase in the hemoglobin's affinity for O_2 and shifts the oxygen-hemoglobin dissociation curve to the left, resulting in greater hemoglobin saturation at lower PO_2s, facilitating the onloading of oxygen in the lung. In the tissues where CO_2 diffuses from the cells into the blood, the opposite occurs: PCO_2 increases and pH falls, shifting the dissociation curve to the right. Under these conditions the affinity of hemoglobin for O_2 is reduced, so the percent saturation of hemoglobin will be lower at any given PO_2, facilitating the offloading of O_2 to the tissues. This is known as the Bohr Effect. An increase in temperature similarly shifts the dissociation curve to the right. During exercise these factors work to increase the oxygen delivery to the muscles. An active exercising muscle fiber generates large quantities of CO_2, increasing tissue PCO_2 and lowering pH. The muscle fibers release several other acids, further driving down pH, and the metabolic heat of exercise can raise muscle temperature 2 °C-3° C. These factors act together to shift the dissociation curve of hemoglobin in the muscle capillaries significantly to the right, allowing an increase in utilization coefficient from 22% to 75%-85% with no decrease in tissue PO_2. DPG is produced by the red blood cells as a product of their anaerobic metabolism. Under hypoxic conditions DPG production increases, shifting the dissociation curve to the right, increasing O_2 release to the tissues. Changes in DPG concentration and its effect on hemoglobin saturation may be an important factor in adaptation to prolonged hypoxia either due to diminished blood flow through a tissue or due to residence at high altitude.

1.2.8. Transport of Carbon Dioxide in the Blood

Although the solubility of CO_2 in water is 20 times greater than that of O_2, only about 7%-10% of CO_2 is transported as a dissolved gas in the plasma (Guyton & Hall, 2000; Marieb & Hoehn, 2007). This is due to the small change in PCO_2 between venous and arterial blood. Venous PCO_2 is normally 45 mmHg, where 2.7 mL/dL of CO_2 is found in solution. Arterial blood leaving the lung has a PCO_2 of 40 mmHg, with 2.4 mL/dL of dissolved CO_2. This small change in blood PCO_2 results in only 0.3 mL/dL of CO_2 being delivered to the lungs in the dissolved state.

The greatest proportion, 70%, of CO_2 is transported in the form of bicarbonate ions. CO_2 combines with water to form carbonic acid, which then immediately dissociates into bicarbonate and a hydrogen ion via the following reaction:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

The formation of carbonic acid from CO_2 and water is reversibly catalyzed by the enzyme carbonic anhydrase in the red blood cells. When the carbonic acid formed in

the red blood cells dissociates, most of the H+ combines with the globin portion of the hemoglobin molecules, which, like all proteins, is a powerful acid-base buffer and prevents a significant drop in blood pH (typically a pH drop of 7.4 to 7.34 is observed between arterial and venous blood). The HCO_3^- moves out of the RBC into the plasma in exchange for Cl^- via a bicarbonate-chloride carrier protein in the membrane of the red blood cell. As blood circulates through the lung, bicarbonate moves back into the red blood cell and Cl^- moves out. The $HCO3^-$ recombines with an H+ and carbonic anhydrase catalyzes the reformation of CO_2 and H_2O, after which CO_2 diffuses down its partial pressure gradient into the alveoli. This is by far the most important means of CO_2 transport in the blood.

The remaining 20% of CO_2 transport occurs through the reversible reaction of CO_2 with amine radicals of the hemoglobin protein to form carbaminohemoglobin:

$$CO_2 + Hb \leftrightarrow HbCO_2 \text{ (carbaminohemoglobin)}$$

CO_2 will combine via the same reaction with plasma proteins, but because hemoglobin is by far the most abundant protein in the blood, carbaminohemoglobin accounts for the majority of CO_2 transport in association with proteins.

Under normal conditions these three methods result in the transport of about 4 mL of CO_2 per 100 mL of blood, or 4 vol%, from the tissues to the lungs. This is actually twice what would be predicted based on the change in PCO_2. The combination of oxygen with hemoglobin in the lungs displaces CO_2 from the blood via two mechanisms known as the Haldane Effect. First, oxygenated hemoglobin has a lower tendency to form carbaminohemoglobin than deoxygenated hemoglobin, displacing much of the CO_2 in the carbamino form from the blood. Second, oxygenated hemoglobin is a stronger acid than deoxygenated hemoglobin. The increased acidity causes it to release H^+, which binds to bicarbonate ions to form carbonic acid, which dissociates into CO_2 and water. As hemoglobin is oxygenated in the lungs, the Haldane Effect facilitates the offloading of CO_2; in the tissues, as hemoglobin gives up its oxygen to the tissues, the movement of CO_2 into the blood is enhanced, effectively doubling the amount of CO_2 transported by the blood.

1.2.9. Internal Respiration

Because the tissues are constantly consuming oxygen and producing carbon dioxide, favorable concentration gradients for the diffusion of O_2 from the blood into the interstitial fluid and CO_2 from the interstitial fluid to the blood are created. Both gases move down their partial pressure gradients, with the peripheral capillary blood quickly reaching equilibrium with the adjacent interstitial fluid (Guyton & Hall, 2000). The partial pressures of O_2 and CO_2 in the interstitial fluid of any given tissue are primarily determined by the blood flow through the local systemic capillaries, the metabolic rate of the tissue cells, and the distance from the nearest perfused capillary. If blood flow through the tissue is decreased, gas transport is decreased, O_2 levels will fall, and CO_2 levels will increase. Similarly, if cellular metabolic rate increases, the consumption of O_2 and the production of CO_2 both increase. Even if average blood flow and metabolic rate are in balance for a tissue so total gas exchange within the tissue is adequate, pockets of hypoxia can exist due to large diffusion distances. The further a cell is from the nearest perfused capillary, the lower the interstitial PO_2 (Rainford & Gradwell, 2006). Because CO_2 diffuses 20 times faster than O_2, it is rarely a limiting factor;

however, for some cells the diffusion distances may become so great the diffusion of oxygen will be too slow to meet the metabolic demands of the cell. The oxygen supply to these cells can be increased either by increasing blood flow through the capillaries, reducing the fall in PO_2 across the tissue space, or by opening more capillaries, reducing the intercapillary distance and, therefore, the required diffusion distance. Normal interstitial PO_2 ranges from 5-40 mmHg, with an average of about 23 mmHg, depending on the above factors (Guyton & Hall, 2000). Because an intracellular PO_2 of only 1-3 mmHg is needed to meet the oxygen requirements of the cell, most cells are more than adequately supplied, and only under conditions such as initiation of exercise before blood flow can be adjusted or extreme muscular exertion are cells forced to utilize anaerobic metabolism.

1.2.10. Control of Respiration

The above sections have taken us through the five stages of respiration from ventilation of the lungs to utilization of O_2 and generation of CO_2 by the cells. For the metabolic requirements of every cell within the body to be met, the respiratory system and its coordination with the circulatory system must be tightly regulated. Regulation of the circulatory system and the control of blood flow to the tissues are discussed in section 1.1. Here we will discuss the control of whole body gas exchange through control of ventilation.

Rhythmic, subconscious ventilation is established and controlled by neural signals from the respiratory center of the brain in the medulla oblongata (Marieb & Hoehn, 2007). Inspiratory neurons in the medulla send motor signals to the diaphragm and external intercostal muscles, which contract and expand the thoracic cavity as described above in the section on ventilation of the lungs. Expiratory neurons of the medulla then fire, inhibiting the inspiratory neurons and stopping the motor signals. The inspiratory muscles relax and passive expiration occurs as the lungs and chest wall recoil. This on-off cycling of the inspiratory and expiratory neurons produces the normal ventilation rate of 12-15 breaths/min. This basic ventilation pattern is modified by another neural center located in the pons. The pons both smoothes the breathing pattern and influences the duration of inspiration and, therefore, the frequency of ventilation (Guyton & Hall, 2000). A strong signal from the pons to the medulla shortens inspiration and, as a result, expiration, increasing the ventilation rate to as high as 30-40 breaths/min, while a weak signal extends inspiration and can slow ventilation to 3-5 breaths/min. Lesions to the pons can retard the switching off of the inspiratory signal, resulting in almost complete filling of the lungs with only short expiratory gasps. Under normal conditions the regulatory influence of the pons is important in fine tuning the breathing rhythm during speech, sleep, and exercise (Marieb & Hoehn, 2007).

> *The <u>rate and depth of breathing</u> are modified in response to changes in the concentrations of CO_2, O_2, and H^+ in arterial blood. Chemoreceptors in the medulla, the central chemoreceptors, and in the aortic arch and carotid bodies at the bifurcation of the common carotid arteries, the peripheral chemoreceptors, send both excitatory and inhibitory signals to the medulla, adjusting ventilation to the changing demands of the body. Of the three, CO_2 is the most important and the most closely regulated.*

Arterial PCO_2 is maintained within +3 mmHg of its normal value of 40 mmHg (Marieb & Hoehn, 2007). CO_2 easily diffuses across the blood brain barrier from the blood into the cerebrospinal fluid, where it is hydrated, forming carbonic acid. As the carbonic acid dissociates, H^+ is released. The cerebrospinal fluid has much less buffering capacity than the blood because it has a much lower protein content, so changes in arterial PCO_2 result in changes in cerebrospinal fluid pH. If arterial PCO_2 increases, cerebrospinal fluid $[H^+]$ increases and pH drops, stimulating the central chemoreceptors in the medulla, which increase the rate and depth of breathing. Increased alveolar ventilation flushes CO_2 out of the lungs and blood drawing arterial PCO_2 and cerebrospinal fluid pH back toward normal. A 5-mmHg increase in arterial PCO_2 doubles alveolar ventilation. Conversely, when arterial PCO_2 is abnormally low, cerebrospinal fluid pH rises and ventilation is inhibited, becoming slow and shallow. Breathing may even stop for a short period until arterial PCO_2 levels rise and stimulate ventilation. Although arterial PCO_2 is the proximate stimulus for ventilation, the central chemoreceptors actually respond to changes in cerebrospinal fluid $[H^+]$, so ultimately ventilation is primarily regulated by pH of the brain.

Changes in blood pH have a much smaller influence on ventilation than changes in PCO_2. Blood $[H^+]$ can increase and blood pH fall due to increased PCO_2 or accumulation of lactic acid during exercise or other metabolic acids in various disease states, but because H^+ cannot cross the blood brain barrier, increased blood $[H^+]$ is not detected by the central chemoreceptors. Changes in blood pH are detected by the peripheral chemoreceptors, however, and a drop in blood pH results in an increase in ventilation rate and depth in an attempt to raise pH by eliminating CO_2 and carbonic acid from the blood. While this regulatory mechanism is much less sensitive than the central pH chemoreceptors, it is faster and may play a role in the initial respiratory response to exercise (Guyton & Hall, 2000).

The peripheral chemoreceptors, especially the carotid bodies, are also sensitive to arterial PO_2; however, arterial PO_2 must drop below 60 mmHg before it significantly influences ventilation rate (Marieb & Hoehn, 2007). This insensitivity to moderate falls in arterial PO_2 makes sense in light of the oxygen-hemoglobin dissociation curve. The percent saturation of hemoglobin and, therefore, the concentration of O_2 in the blood remain high until PO_2 falls below 50-60 mmHg. At PO_2s of 60 mmHg, the peripheral chemoreceptors stimulate the medulla to double the ventilation rate and depth and can increase ventilation as much as fivefold at very low PO_2s when PCO_2 and pH are at normal levels (Guyton & Hall, 2000). When a person ascends to altitude and arterial PO_2 falls below 60 mmHg, ventilation is stimulated, which increases O_2 levels in the alveoli and transfer of oxygen to the blood, but it also decreases alveolar and blood CO_2 and raises pH, both of which inhibit ventilation. As a result, a balance of excitatory and inhibitory stimuli is reached with the increase in ventilation due to hypoxia being somewhat less than expected if CO_2 and pH were held at normal levels. With prolonged exposure to altitude, ventilation increases beyond this initial response due to reduced sensitivity of the central chemoreceptors to low PCO_2 and adjustment of body fluid pH by the kidneys. Over a period of 2-3 days of acclimatization to altitude, the inhibitory effect of low PCO_2 is diminished and the stimulatory effect of low PO_2 becomes more prominent, resulting in up to a four- to fivefold increase in alveolar ventilation. This is one reason mountain climbers ascend high peaks in gradual stages, to allow the body's respiratory control functions to acclimatize to progressively greater altitudes.

In addition to the chemical regulation of respiration, higher brain centers can also influence ventilation. The hypothalamus modifies ventilation rate in response to strong emotions or pain (Marieb & Hoehn, 2007). Excitement and stress typically increase ventilation rate. We also have conscious voluntary control of our breathing via the cerebral cortex. Voluntary inputs bypass the medulla, stimulating the ventilatory muscles directly. Our ability to consciously hold our breath or hyperventilate is limited, however, because the medulla will reestablish control of ventilation if blood PCO_2 reaches critical levels. In an effort to maximize their time underwater, breath hold divers will often voluntarily hyperventilate before holding their breath and submerging. This practice can be dangerous, resulting in what is known as shallow water blackout. Voluntarily hyperventilation reduces alveolar and blood PCO_2, diminishing the CO_2-driven urge to breathe. When divers descend they consume oxygen from the lungs and blood but do not feel a need to return to the surface until CO_2 levels build back up. When divers do ascend after a prolonged breath hold, PAO_2 in the lungs rapidly decreases to potentially critical levels due to the decreased water pressure on the body, resulting in a loss of consciousness and possible drowning.

Finally, the respiratory response to exercise is complicated and still not fully understood (Marieb & Hoehn, 2007). During exercise the muscles consume large amounts of oxygen and generate large quantities of CO_2, and ventilation can increase 10- to 20-fold to deal with these demands, but the respiratory response to exercise does not seem to be driven by changes in arterial PCO_2, PO_2, or pH. As exercise begins, ventilation increases abruptly then continues to increase gradually until it plateaus at a steady state. When exercise stops, there is a small abrupt drop in ventilation followed by a gradual return to a normal breathing rate. Throughout this pattern of respiratory adjustment, arterial PCO_2 and PO_2 are virtually unchanged, suggesting that neither PCO_2 nor PO_2 changes stimulate the respiratory response. The most widely accepted hypothesis suggests that the abrupt increase in ventilation at the beginning of exercise is due to the combined effects of (1) a conscious anticipation of exercise, (2) simultaneous stimulation of the respiratory center by higher brain centers in conjunction with motor activation of skeletal muscles, and (3) excitation of the respiratory center by proprioceptors in the muscles, tendons, and joints. The combination of these neurogenic mechanisms produces the initial increase in ventilation, then the gradual increase and plateauing of breathing rate matches ventilation rate to the production of CO_2. Similarly, the abrupt drop in breathing rate at the end of exercise is believed to be due to a cessation of these neurologic inputs followed by a gradual decrease in ventilation as CO_2 flow decreases and O_2 debt is repaid. The generation of an oxygen debt, that is a buildup of lactic acid in the muscles and interstitial fluid due to an inability to deliver sufficient oxygen to working muscles to support aerobic metabolism, is not due to an inability of the lungs to provide enough oxygen, as hemoglobin leaving the lungs is fully saturated even at maximal exercise. Rather oxygen debt is due to cardiac output and muscle vascularization limiting the amount of blood that can be circulated through the muscle. This should make it obvious that breathing 100% oxygen at sea level during athletic events does not improve oxygen delivery to the muscles or speed the payback of oxygen debt because the blood is already carrying virtually all the oxygen it can. The problem is in the amount of blood that can be delivered to the muscles. At altitude, however, low PAO_2, reduced hemoglobin saturation, and, therefore, reduced O_2 content of the blood can contribute to reduced exercise capacity, which can be helped by supplemental oxygen.

1.2.11. Summary

This chapter attempts to select and summarize key concepts of respiratory anatomy and physiology from three respected texts that are of particular importance and interest to the aerospace Physiologist. For further study of pulmonary anatomy, refer to Marieb & Hoehn. Guyton & Hall provide a detailed treatment of all of the respiratory physiology topics touched on in this chapter and many more. For a detailed examination of the respiratory consequences of the stressors associated with the aerospace environment, including hypoxia, anti-G straining maneuver, and positive pressure breathing, refer to Rainford & Gradwell.

References

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Concepts

- Alveolar gas equation
- Gas exchange in the lung, 1.2.5.
- Oxygen-hemoglobin dissociation curve
- Primary function of the respiratory system
- Rate and depth of breathing

Vocabulary

- PAO_2
- Alveoli
- Bohr Effect
- Carbonic anhydrase
- Cellular respiration
- Diffusion
- Eustachian tubes
- FIO_2
- Intercostal muscles
- Larynx
- Oxyhemoglobin
- Pharynx
- Pulmonary ventilation
- Trachea

1.3. Nervous System

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In flight, aircrews are in a "noisy" sensory environment. Attention resources may be directed to aspects of flight tasks that exclude other relevant stimuli. In some circumstances, central nervous system stimuli with intensities many times greater than those found in ground environments can fail to be detected. Whether it is a visual task suppressing diminished contrast sensitivity or pressure breathing for G-forces that overwhelm the sense of fatigue in the muscle of respiration, an understanding of the physiological function of the autonomic nervous system (ANS) provides a good foundation to build one's knowledge of performance in a complex environment.

> *Autonomic function is that portion of the nervous system that commands visceral functions. Activities like blood pressure, heart rate, core temperature, pupil response, sweat glands, and digestion are controlled "automatically" without conscious attention.*

The self-governing effects over organs and systems are fully challenged in the aviation environment, especially as increasing numbers of aircraft systems are displayed on man-mounted devices. Appropriate human function is governed by ANS functions that are divided into two subgroups: the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS). The ultimate in task management, each system contains motor neurons and sensory neurons that act like the auto-pilot to elicit changes to systems in the body. The functions related to fight or flight are considered basic to sustaining life, so it is no surprise that the centers for ANS control are found in the most evolutionally primitive regions of the central nervous system.

1.3.1. Integrated Control of the Autonomic Nervous System (ANS)

The context of this chapter is really centered on the human responses controlled by the ANS during task completion in any advanced setting. Automated procedures are the lifeblood of aircrew when successfully completing BOLDFACE during an emergency. When tasks are practiced with a consistent procedure, the search time and error rates are virtually eliminated. How does a trained skill correlate with an automated process? Can a human acquire autonomic stimuli and control the input? A sensor in a weapon system constantly updates information about distance and speed (for example) to onboard computers just as the CNS receives updates without conscious control throughout the day.

The relatively sophisticated information transmission and processing of the CNS frees up higher centers of brain functions to deal with other conscious activities. Arterial blood pressure can be raised significantly by signals from the hypothalamus routed through the cardiovascular control centers. Similarly, body core temperature, altered salivary and gastrointestinal activity, and bladder emptying can also be controlled by hypothalamic stimulation. For an aircrew member in the middle of running an emergency procedure (BOLDFACE), the alteration of physiological function could diminish the capacity to continue the fight. Instances of emotional agitation have been known to produce problems such as stomach ulcers, constipation, and heart dysrhythmias. A short description of the effects on primary organ follows:

Heart: The sympathetic and parasympathetic nervous systems have an antagonistic relationship with respect to cardiac regulation. The SNS increases cardiac efficiency by increasing both heart rate and contractile force. Some mild dilation of coronary vessels that supply the heart with blood occurs, which, in turn, increases cardiac metabolism. The PNS decreases cardiac pumping capability by reducing heart rate and cardiac metabolism.

Vascular System: Blood pressure measured in the vascular system results from the interaction between the force of blood propulsion by the heart and the resistance to blood flow by vessel walls. The SNS influences this relationship through increases in ejection pressure and stroke volume of the heart and can increase the tone of the vasculature through vasoconstriction.

Lungs: Innervations to the lungs from both the SNS and PNS are minor, although SNS stimulation may cause bronchial dilation, whereas impulses from the PNS cause bronchial constriction and an increased bronchial glandular secretion.

Skin: Blood flow to the skin, sweating, and erection of the hairs on the skin are three primary effects of the ANS on this organ. The SNS alone works to cause contraction of the piloerector muscles, resulting in the "hair on the back of your neck" to stand up, typically associated with body core temperature drop and subsequent shivering. This effect is also associated with rage and fright. In response to SNS stimulation, the sweat glands increase production, although the origins of impulses that stimulate sweat glands lie in the hypothalamus, which is frequently associated with PNS function.

Eyes: The ANS exerts control over two functions of the eye: pupil size and visual accommodation by adjustment of the shape of the lens. When bright light enters the eye, the parasympathetic reflex is engaged to reduce pupil size by contracting the circular muscles of the iris. The sympathetic response in a darkened environment causes pupil dilation through sympathetic stimulation of the meridional muscle fibers of the iris. Visual accommodation is nearly exclusively under the control of the PNS, for example, when the lens is adjusted for distant vision and held in a flattened shape by the tension from surrounding suspensory ligaments. Lens accommodation is achieved by PNS stimulation, which contracts the ciliary muscle and releases tension on the suspensory ligaments, increasing the convex shape of the lens. The advent of visor-mounted displays and advanced use of night vision devices has heightened the need to better understand these actions for both engineering and employment of the technology.

1.3.2. The Big Picture

Higher mental functions of the central nervous system often override those automated responses described in this primer. Simple reflex actions produce adjustments to system responses in an effort to control the physiological activity. For instance, when one is running away from danger, changes in heart rate, respiratory rate, and sweat rate may go unnoticed until the danger has subsided. Individual parasympathetic and sympathetic responses are well documented through heart rate,

pupil dilation, respiratory rate, and other objective measures. Additionally, increased sympathetic cardiac tone may be accompanied with increased plasma noradrenaline and muscle sympathetic activity. An example of sympathetic nervous system stimulus has been measured during helicopter underwater escape training (HUET). The anxiety and physical activity related to the HUET likely trigger the sympathetic stimulation rather than the actual submersion in cold water. No matter the environmental "cue," the response of the nervous system is often tied to some effect not predicted in the mission preparation. When man-mounted systems are designed, human factors engineers must consider the mechanics of the ANS and metabolic changes associated with activation of systems. Although humans are not adept at perceiving sensory resolution, or strength and speed of motor responses, we use our nervous system for effective interactions with the environment. The signals processed in the ANS generally precede the subjective phenomena of perception, awareness, and consciousness. In a visual example, consider the ability to differentiate between shapes depicted on a display. The process begins with visual point receptors in the central part of the retina, moves through the visual processing centers of the brain, then ends up at a cerebral point where the decision to accept or reject the image as a target of interest is made. Now consider the "accept" and "reject" processing time of a three-dimensional object viewed from various angles. How is the perception different from the analysis of the two-dimensional display? In the case of the 1970's era F-15 fighter (Fig. 1.3.2-1), the steam gauge approach to displaying engine instruments, weapons, and communication/navigation presented a highly saturated visual field to augment the pilot's view of the world outside the cockpit. The 21st century ushered in the current generation of glass cockpits (e.g., Typhoon, Eurofighter) (Fig. 1.3.2-2), wherein the status displays are condensed to a small array of color multifunction displays.

Figure 1.3.2-1. F-15 Cockpit

Figure 1.3.2-2. Typhoon Cockpit

The sensory load is potentially less demanding, as the displays are drawn into three or four central reference points, made larger, and augmented with color for ease of interpretation. The next step in the progression of minimizing visual sensory load is found in the Joint Helmet Mounted Cueing System (JHMCS) (Fig. 1.3.2-3). In addition to the cockpit-mounted panel Visually Demanding Visual 'Clean' Joint Helmet displays, relevant navigation, weapons, and aircraft status are displayed at near-vision field on the visor of the helmet, thus allowing the pilot to retrieve information without regard to direction of gaze. Sensory information is not, of course, limited to visual stimulation.

Figure 1.3.2-3. Mounted Cueing System

Auditory signals – processed in the parameters of amplitude and frequency – are another area of concern in aviation. One of the most common auditory warnings is the ambulance “siren.” It cuts through traffic noise and commands one's attention, but it does so by sheer brute force. This “better safe than sorry” approach to auditory warnings occurs in most environments where sounds are used to signal danger or potential danger. In the U.S. Air Force (USAF) KC-135 Stratotanker, the gear warning horn is a derivative of a truck horn that has a similar effect. Flooding the environment with sound is certain to attract attention; however, it also causes startled reactions and prevents communications at a crucial point in time (Patterson, 1982). Processing the strength or loudness of auditory signals in the ANS is interpreted over approximately 200 ms, effectively a summing of the energy of the sound. When presented continuously, the loudness of the tone diminishes over time and may be interpreted as “less urgent” (Proctor, 1994). In addition to amplitude, frequency and the association with particular conditions must also be considered in designing warning systems that will stimulate the auditory processes. The number of immediate-action warning sounds should not exceed about six, and each sound should have a distinct melody and temporal pattern. When fully integrated to an aircraft, the frequencies of sounds must be adjusted to different intensity levels to prevent masking, or covering up. Masking tones may result in signal loss or “missing” a warning tone in a cacophonous environment.

Signals carried through the CNS do not stop once formal analysis is complete. Consider another visual example: emit a light into the eye and watch the resultant changes in pupil diameter – pretty basic ANS responses to light. But continue shining the light and note whether the pupil diameter changes, is locked into position, or begins to oscillate. How is the response in the pupil affected by the intensity of the light or length of time presented? Many of the actions present during the previous example are unrelated to the original event of interest. The challenge is to isolate the relevant information from the irrelevant information that arrives with it (Partridge, 1993). The conflict that arises in the CNS could introduce sensory conflicts that may lead to errors. Man-mounted equipment that employs a signal through the ANS may introduce conflicts in sensing multiple simultaneous events. The signal detection theory addresses the sensory thresholds required to identify a signal (Garland, 1999). The sensitivity to detect differences between two signals can be measured and applied to more advanced scenarios like recognition memory, vigilance, and allocation of mental resources. Clearly, in a highly saturated flight environment, discrimination of signals of interest can be overwhelmed by signals with greater strength but less relevant meaning. The more alternatives there are to distinguish, the better the signal-to-noise ratio needs to be. The International Phonetic Alphabet and standard air traffic control

language are methods designed to maximize the signal-to-noise ratio and improve processing (Bailey, 1989).

The core understanding of neurophysiology is more complex than a single chapter can capture, but as with other features of aviation physiology, the practitioner of the specialty must concentrate on applied physiology. The human placed in a complex system must perceive the locations of objects and signals in a two- and three-dimensional space. Interpretation of signals must be accurate and timely to prevent disaster or embarrassment. The basic constructs of perception and function of the nervous system help to propel us toward a better understanding of stimulus organization, patter recognition, and selection of response.

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Concepts

Autonomic function

Vocabulary

Central nervous system (CNS)
Autonomic nervous system (ANS)
Parasympathetic nervous system (PNS)
Sympathetic nervous system (SNS)

1.4. Vision

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1.4.1. Introduction

Early aerospace medicine pioneers Col W.H. Wilmer and Maj Conrad Berens (1920) wrote: "Of all the physical qualifications necessary for the military aviator there is not one that is more important than good sight." This aeromedical insight has been proven true many times over. It is commonly accepted that more than 80% of the sensory information necessary to accomplish the flying mission is gathered by the visual system, even in modern technically enhanced aircrafts. Accordingly, USAF aviators are selected, in part, on excellent visual ability and are periodically evaluated to ensure continued optimal visual capability.

However, not all aircrew begin and end their career with so-called "perfect" vision. Perfect vision assumes visual acuity is as sharp as humanly capable at distance and near. It also assumes both eyes are equal in performance and a given person will correctly perceive a visual scene. Some aviators do, in fact, have virtually ideal visual capability as dictated by the selection standards. Most, however, have minor visual imperfections that are typically easy to compensate. As a result of relaxed aeromedical vision standards to allow more aircrew candidates and as trained aircrew simply get older, approximately 40% of all aircrew including pilots require some form of vision correction for flight duties.

Aviator visual performance is further challenged by utilization of devices designed for vision enhancement and/or protection that may, in fact, alter the normal visual perception. For example, visors/spectacles designed to protect eyes from laser threats can mask or alter critical color cues. Even clear chemical/biological or eye hazard protection lenses can create spatial orientation anomalies caused by prismatic effects, effectively altering an aircrew's situational awareness.

The flying environment itself presents challenges to normal visual performance, ranging from physical dynamics created in flight by gravitational forces (G-forces), fatigue, and hypoxia to visual dynamics such as compressed visual processing time due to aircraft speeds, absence or misleading visual cues, and multiple nonredundant or conflicting sources of spatial information.

This chapter provides a basic understanding of the vision principles that contribute to the efficiency and effectiveness of USAF flying personnel. Psychophysiological and physical aspects related to aircrew vision are applied. By design, information presented is not an exhaustive reference of the human vision but rather selected details presented to assist in understanding. Complete information about the function, anatomy, and physiology of the eye and its neurological interactions can be found in appropriate references.

1.4.2. Form and Function of the Eye

One core concept to understand aviation vision is that all vision occurs peripherally at the eye and centrally in the brain. The eye is, in essence, a device to capture information, while the brain is the information decoder. If the eye doesn't capture critical visual information, then the brain cannot make judgment and action based on that missing visual stimuli (i.e., not looking where necessary). Conversely,

the eye may capture the "right" stimuli, but the brain may not attend to that information or may make judgment based on other sensory input.

It is also important to understand that conversion of visual stimuli and subsequent action based on visual inputs occur in steps: presence of electromagnetic energy, capturing and conversion of that energy to a neurological signal, transfer of the signal to the brain for interpretation and integration with other sensory input, and finally action taken based on the information.

The eye is a system of elements that focus light energy onto a systematic pattern of cells, which photochemically convert energy into neurological signals transferred to the occipital area of the brain for processing and interpretation as vision. The interpretation of the visual input is then integrated with other sensory sources and then acted upon as necessary.

Each eye is contained in a bony orbit, which provides both protection and support of the globe (Fig. 1.4.2-1). The bony orbit is configured like a quadrilateral pyramid, which allows the anterior portion of the eye to be exposed with a wide aperture. The posterior portion of the bony orbit tapers down to an opening at the apex. The posterior opening allows the cranial nerves and blood supply to communicate with the eye. The eye is aligned and moved by six extraocular muscles, which, except for one (the inferior oblique), take their origin from a fibrous ring, the annulus of Zinn, located at the bony orbit's apex. The eye itself sets in Tenon's capsule, which acts as an articulate socket. The remainder of the space in the bony orbit is completely filled with fat pads.

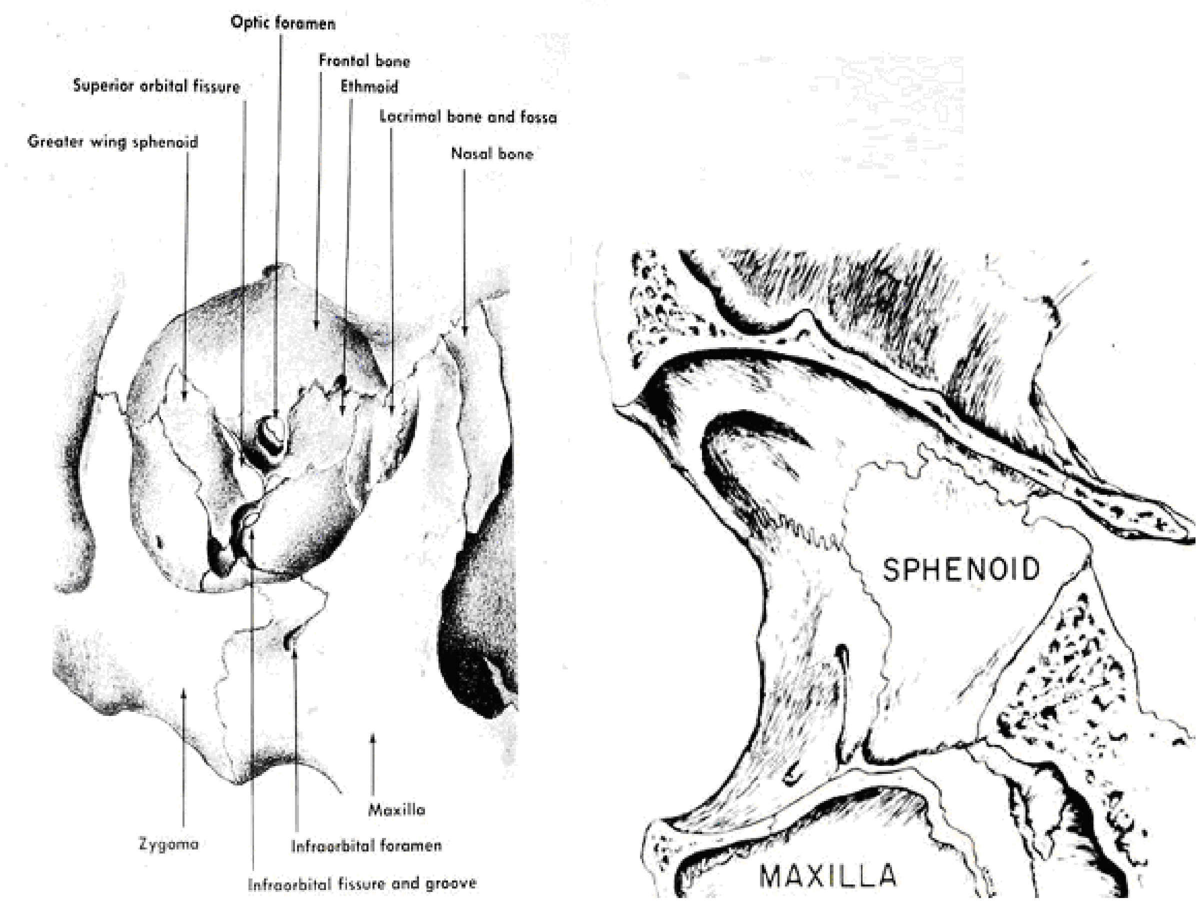


Figure 1.4.2-1. Bony Structure of the Eye

The eye globe is approximately 1 in. (25 mm) in diameter and consists of three layers (Fig. 1.4.2-2). The outer two layers support, protect, and provide nutrition. The outermost layer, the sclera, is a tough, fibrous coat of collagen bundles laced together in an irregular pattern, which makes the sclera appear white. The anterior portion has a bulge about 12 mm in diameter called the cornea. The cornea is composed of collagen fibers similar to the sclera but formed into a regular pattern of parallel fibers, creating the transparent surface. This is the "window" that allows electromagnetic energy to enter. The shape of the cornea, in combination with the indices of refraction (refractive density), cause the initial focusing of electromagnetic energy (within a limited range of energies) on the retina. In fact, the cornea and its overlying tear film are the most powerful components in the ocular refracting system.

The interior to the scleral layer, the uvea, is the pigmented vascular layer of the globe. The anterior portion of the uvea forms the iris or colored part of the eye. The iris color is a function of the degree of pigmentation. For example, brown eyes are heavily pigmented, while blue or green eyes are relatively lightly pigmented. The iris forms a circular opening, the pupil, observed as the black center of the anterior eye. Part of the iris's function is to control the amount of electromagnetic energy entering the eye by constricting or dilating the size of the pupil. The posterior portion of the uvea nourishes the outer sclera and the innermost layer, the retina.

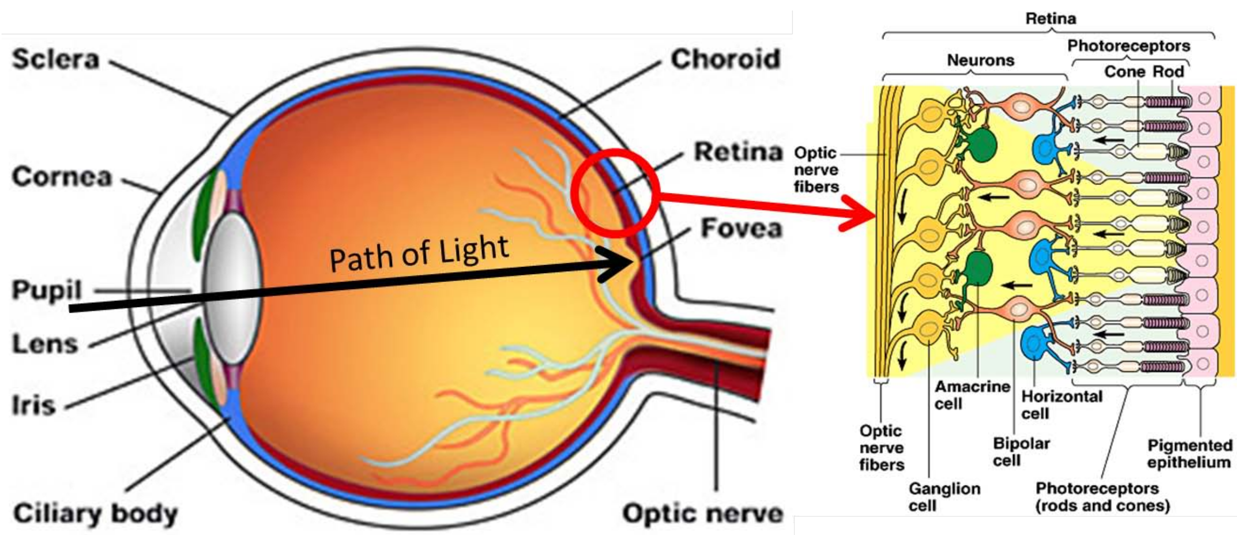


Figure 1.4.2-2. Anatomy of the Eye

Immediately behind the iris is the crystalline lens. The purpose of the crystalline lens is to increase the optical power of the eye's focusing system, also called accommodation. Physically it's about 9 mm in diameter and 4 mm thick. In a person with "perfect vision," distance vision is focused when the crystalline lens is in its natural relaxed state, i.e., no accommodation. When that person's attention is drawn to a close object, constriction of the ciliary muscle causes the crystalline lens to thicken, increasing the refractive power (accommodates) to maintain a clear focused image. This action of accommodation applies to those whose distance vision is corrected by spectacles, contact lenses, or refractive surgery. In youth, the crystalline lens is quite flexible. Over time accommodative flexibility will gradually decrease. About age 40, the flexibility has decreased sufficiently to affect its ability to accommodate to normal

reading distance. This condition is called presbyopia and continues a progression of reduced accommodative power until about age 65.

The retina contains the elements (rods and cones) that convert electromagnetic energy into neurological signals. This retina actually consists of two layers. The outer layer where the rods and cones are positioned is nourished primarily by the vascular uvea. The innermost nerve fiber layer of the retina is nourished by retinal blood vessels. This difference in metabolic support plays a role in the visual response to high-G exposures that will be discussed later. Visual light energy must pass through the nerve fibers, scattering the energy, before they are captured by the photosensitive cells. It would seem that the retinal layers are opposite to optimal engineering design. This certainly impacts the resolution potential of the eye. However, there are two factors that reveal the advantages of the retinal design. First, the photoreceptors have a high metabolism demand, higher than the neural cells. This high nutritional demand is met by the close proximity of the vascular uvea. Second, the optics of the eye focus light energy to a central area of the retina called the fovea or macula. In the foveal area, nerve fibers are dramatically thin, enabling this area to provide the eye's sharpest vision.

The retina consists of two classes of photosensitive cells, rods and cones, and various interconnecting nerves. There are three cones types: those sensitive to short (blue), medium (green), and long (red) wavelengths. There is only one rod type, which is sensitive to a range of wavelengths in the middle of the cone sensitivities. The two classes combine to give the human visual system a tremendous operating illumination range from very bright (photopic) to very dim (scotopic) conditions. Additionally, the two classes of photosensitive cells perform different functions and are distributed in different density patterns. This will be discussed later.

The retinal photosensitive cells convert electromagnetic energy into neurological signals. These signals are passed along nerve cells, which merge into a bundle of nerves called the optic nerve, exiting through an opening in the posterior globe. The optic nerve bundle of one eye continues back, intertwining with the optical nerve bundle from the other eye to the occipital area of the brain. The occipital area of the brain decodes the neurological signal and begins the interpretation and action of the visual input.

As a final consideration of form and function, normal human vision includes two "redundant" eyes for capturing and converting electromagnetic energy. In part, two eyes provide us with a survivability aspect should one eye be injured or lost. However, if both eyes are functioning equally, the visual information from each eye is combined and processed, giving rise to higher visual performance than possible from a single eye system. In other words, combined two-eye interpretation (binocular) is better than each individually (monocular). Each eye views the environment with a slightly different perspective caused by the physical horizontal separation of the eyes. When an object is selected as the point of attention, that specific point of attention is placed on corresponding locations on each retina, a common reference point. Other points of interest located at equal corresponding locations are judged to be in the same plane in space. Points of interest that result in disparate placement on the two retinas are judged to be further or closer. See Figure 1.4.2-3 below. The advantage and limitations of binocular and monocular vision will be discussed later.

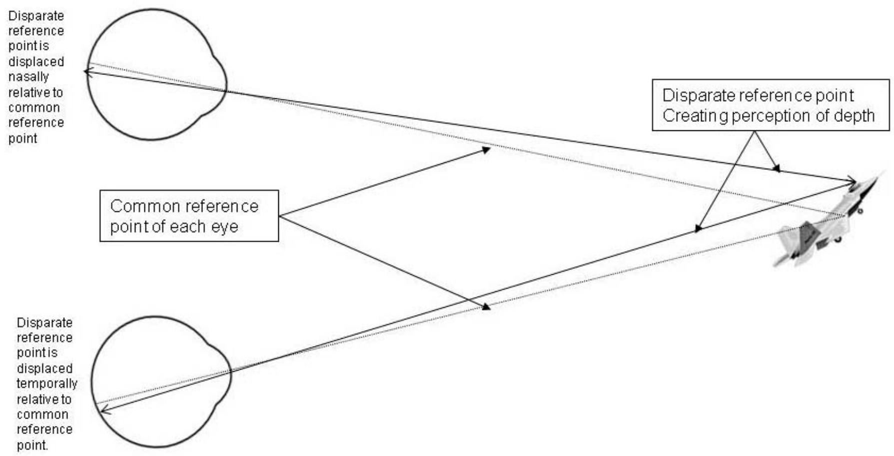


Figure 1.4.2-3. Binocular Perception

1.4.3. Photosensitive Cells (Rods and Cones)

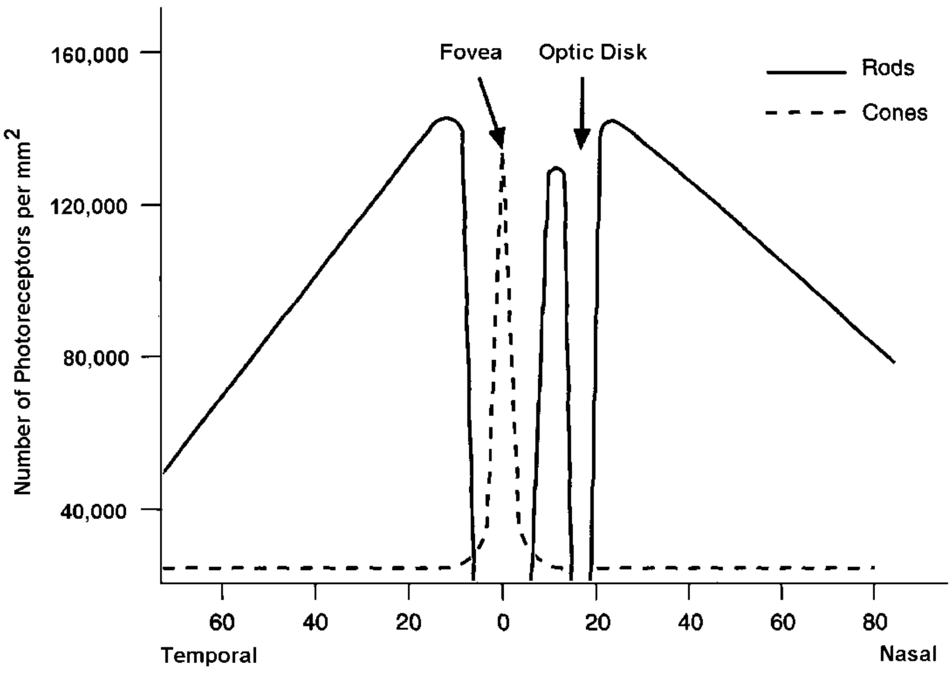
Electromagnetic energy spans a wide range of wavelengths. Very short wavelengths (ultraviolet (UV), gamma, and x-rays) and very long wavelengths (infrared, microwave, radio) do not stimulate human photosensitive cells and are therefore invisible to humans. The narrow range of mid-wavelengths that do stimulate these cells is referred to as visible light (peak sensitivity for color vision is at 555 nm).

Normal human color vision results from the stimulation of cone cells (one or more of the three cone cells types). Cone cells sensitive to short visible wavelengths perceived as "blue" light (peak at 440 nm) are called "blue" cone cells. Cone cells sensitive to medium visible wavelengths perceived as "green" light (peak at 535 nm) are called "green" cone cells. Photosensitive cells that give perception of "red" light (peak at 570 nm) are called "red" or long-wavelength cone cells. Other color perceptions result from stimulating more than one cone cell type (stimulating both red and green cone cells is perceived as a "yellow" light) or from the relative lack of a given wavelength (a filter that removes blue wavelengths from a full spectrum light will make the light appear yellow). In humans, there are twice as many "red" cones as there are "green" cones. There are 10 times as many "red" and "green" cones as there are "blue" cones.

The rod system of photosensitive cells is stimulated by a narrow range of wavelengths between the blue and green cones (peak at 510 nm). However, there is only one rod cell type. As a result of the single-rod cell design, the rod cells are either stimulated and thereby give a "vision" response or they are not stimulated and give a "no vision" output. There is no wavelength discrimination as found in the cone system and consequently no rod color perception.

Cone cells are closely packed together in an area called the macula and become more widely spaced peripherally. It's this dense array of cone cells in the macula that gives rise to the high resolution portion of our vision. Cones are linked to the occipital portion of the brain in a one-cone-to-one-nerve pathway. The combination of one cell to one nerve pathway along with the densely packed central retina cone pattern (macula) enables the eye to have very high resolution. Stimulation of a single cone enables very accurate location of the stimulating source, but at the expense of sensitivity. Cones, compared to rod cells, are relatively insensitive and correspondingly

work best in daytime or simulated daytime light (high illumination). In general, the cone system is used to detect color and for fine image resolutions, (i.e., I am looking at what?). Rod cells, in contrast, are more sensitive to appropriate visible light and are interconnected by common nerve paths. A one-rod-cell-to-many-nerve-paths configuration along with high sensitivity make the rod system more responsive to detecting a dim light source (just stimulating one cell sends a signal along many nerve paths). Rod cells are absent in the center of vision (the fovea), are most dense around the macula (parafoveal), and become less dense in the peripheral retina. The rod system sacrifices accuracy in spatial location of the source for sensitivity. In general, the rod system is used to detect motion or the "something happened" (i.e., I am looking where?). The distribution of the rods and cones (Fig. 1.4.3-1) is important in aviation vision and will be further discussed later.



Retinal distribution of rods and M- and L- cones (Osterberg, 1935).

Figure 1.4.3-1. Retinal Distribution of Photoreceptors in the Human Eye

1.4.4. Visual Acuity

In 1862, Snellen devised a method of measuring visual acuity using black letters on a white background. He chose black on white simply because this form could be reliably obtained in a standard and consistent form from a printer. Snellen used the concept that all focused light entering the eye crosses an optical nodal point. Light rays from the extreme opposite edges of a target will cross the nodal point and form a visual angle (Fig. 1.4.4-1). As the target approaches the eye, the rays at extreme target edges will subtend a larger visual angle, forming a larger image on the retina. Snellen found that the smallest letter that could be seen by most visually normal patients at 200 feet was about 9 cm tall and composed of lines about 1.8 cm wide. Similarly, the smallest letter seen by normal patients at 20 feet was 0.9 cm tall with 0.18 cm lines. Both targets subtend a visual angle of about 5 arcminutes. The lines had a minimum

separation of 1 arcminute (1/60th of a degree). This was consistent with the understanding at that time as determined by ancient astronomers that two stars had to have about 1 minute of angular separation to be distinguished as two separate bodies. Snellen concluded that the minimum visual angle was therefore 1 arcminute. Since that time, standard chart design has used letter targets with line and space widths of 1 arcminute, for example, the letter "E" with three horizontal lines that are 1 arcminute wide and separated from each other by 1 arcminute of space. The total letter height is 5 arcminutes.

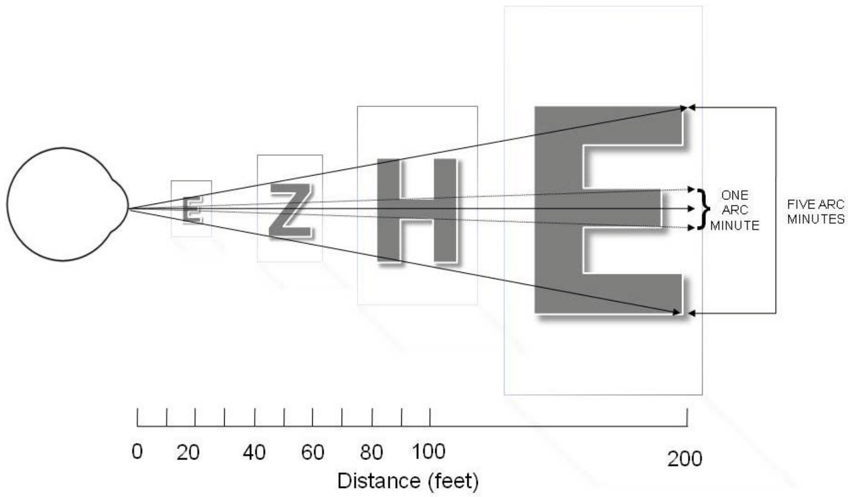


Figure 1.4.4-1. Snellen Visual Angle

Snellen expressed visual acuity as a fraction of normal as follows:

$$\text{Visual acuity} = \frac{\text{Distance at which a person can read a letter}}{\text{Distance at which a person with normal acuity should be able to read a letter}}$$

In other words, the bottom number is the distance from which the chart is designed to be viewed. The top number is the distance to which the patient must move relative to the chart to recognize the same letter that a normal person should see.

$$Normal\ visual\ acuity = \frac{20\,ft}{20\,ft}\ or\ \frac{6\,m}{6\,m}$$

which equates to a minimum visual angle of 1 arcminute.

$$Nearsighted\ visual\ acuity\colon\ \frac{10\,ft}{20\,ft}$$

indicates the person must move closer and is, therefore, nearsighted.

One method to use the Snellen letters is to create a chart of letters all equal in size. To measure visual acuity, the person would simply walk forward until he/she could read the letters. The distance is measured and visual acuity is determined. The Navy (USN) used this method for many years.

Currently all U.S. military services (and civilian examiners) use a chart with letters of various sizes placed at 20 feet or in an optical device that simulates 20 feet (Fig. 1.4.4-2). The numerator is always 20 under these conditions. A 20/20 letter on this chart subtends a visual angle of 5 arcminutes; a 20/200 letter subtends a visual angle of 50 arc minutes. The latter visual acuity indicates that a person viewing from 20 feet can identify letters that a normal person could see at 200 feet.

The Snellen visual acuity test was developed in 1862 by Hermann Snellen and is designed with high contrast black letters on a white background, ideal conditions rarely found in the natural world and in particular in the aviation environment. As the contrast of a target against its background decreases, visual performance will degrade. Currently, there is no standard for contrast measurement or performance level. With the assumption that vision performance will degrade under certain conditions, aircrew are required to meet strict standards and should perform their duties with optimally corrected vision.

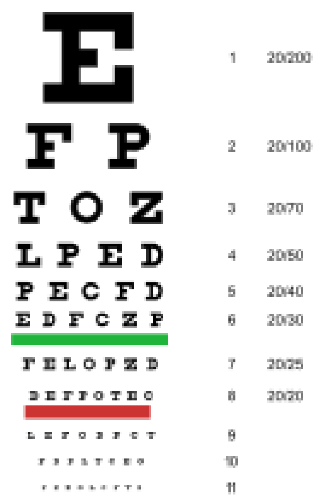


Figure 1.4.4-2. Snellen Visual Acuity Test Used by the Military

1.4.5. Lag in Perception

Visual perception is also affected by cell physiology. Conversion of electromagnetic energy to a neurological signal and its subsequent interpretation don’t happen instantaneously. While the process is amazingly quick, there is a time lag. Review the figure below (Fig. 1.4.5-1). Note the time increments. The time to detect an event can be very short. The highly sensitive rod system detects a change in the field of view. Due to the relatively poor resolution of the rods, there may be no information about what changed. To determine “what” changed, the high resolution cone system is directed toward the event, and the subsequent perception is processed. The longest period of time is the decision-making process needed to make a decision on the appropriate action to take relative to the perceived event. This occurs in the brain and then some input is given to the aircraft controls followed by the aircraft response.

To illustrate this time lag, imagine you are flying. Something catches your attention (rods detection motion). You look toward the area of the motion to determine what is happening. About 1 s later you determine there is another aircraft approaching. You take 2 s to determine to bank left and up. The aircraft reacts to your control input and responds as directed. If you are flying at 1500 kt, you will have traveled about 23 nmi between detecting some motion and the aircraft’s initial response. If you are

traveling at 3000 kt, you have just covered 44 nmi. And that is on a good day! Now consider the other aircraft might be flying at a similar rate. If you assume the other pilot doesn't react at all, within a little more than 3 s you both have traveled a net distance of 88 nautical miles before your "quick" action and agile aircraft begin to respond. Add to the situation hypoxia or inattention and the zone of safety must become much greater to avoid a mishap.

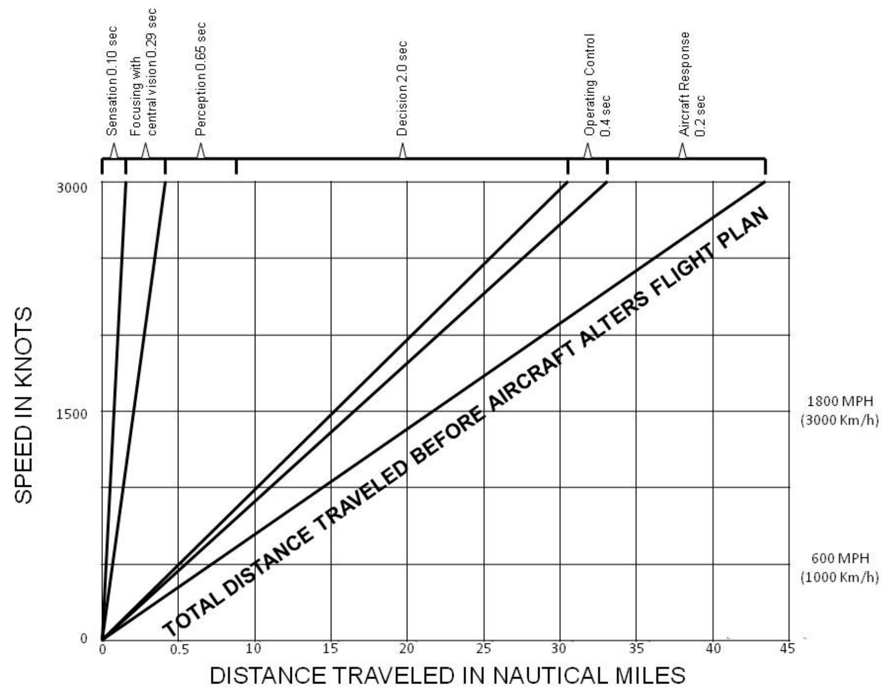


Figure 1.4.5-1. Reaction Time

1.4.6. Environmental Influences on Vision

1.4.6.1 Effects of Hypoxia on Vision. Hypoxia can cause several changes in vision. Visual disturbances may occur at any altitude above sea level. The *indifferent zone* is a range between sea level and 10,000 ft. Within this range, daytime vision (photopic vision) is not significantly affected as most targets of information are generally high contrast and with high illumination. For USAF aircrew, supplemental oxygen is not required when flying below 10,000 ft. There is, however, a slight impairment of night vision (scotopic vision) when targets of information are lower in contrast. For this reason, it is imperative for night combat flyers to use supplemental oxygen from the ground up.

The zone of adaptation ranges between 10,000 and 16,000 ft of altitude. At these altitudes, unpressurized flight with no supplemental oxygen will impair visual function. The following ocular changes occur, becoming more marked with increasing altitude:

a. Retinal vessels appear dark due to the cyanotic condition.
b. The diameter of the arterioles increases 10%-20%.
c. Retinal blood volume increases up to four times normal.
d. Retinal and systemic arteriolar blood pressure increase.
e. Intraocular pressure increases with the increase in blood volume.

f. Pupils constrict.
g. At 16,000 ft, 40% of night vision ability is lost.
h. Ocular accommodation and binocular convergence decrease.
i. Ability to maintain binocular alignment diminishes.
j. Visual reaction time is reduced.

All these changes return to normal by either use of supplemental oxygen or with return to ground level.

The zone of inadequate compensation is the region between 16,000 ft and 25,000 ft. In this zone, one or more of the above changes become severe enough when exposed to unpressurized flight and no supplemental oxygen to significantly interfere with visual performance. Visual reaction time is significantly slowed and motor response to visual stimuli is sluggish, as all mental processes are affected. Double vision may result from binocular eye misalignment for which compensation would normally adjust. Loss of accommodation and convergence will result in the inability to clearly interpret cockpit instrumentation. All changes are reversible by use of supplemental oxygen or returning to ground level.

Finally, the zone of decompensation or zone of lethal altitude occurs above 25,000 ft. In this zone circulatory collapse occurs and there is loss of both vision and consciousness. As a result of neuron death from severe hypoxia and lack of circulation, the aviator may suffer permanent damage to the retina and brain.

1.4.6.2 Brightness of the Field of View. The amount of light reflected back to the eye determines the overall brightness of the individual's field of view. Snow, for example, reflects back 85% to 90% of the light falling on it. White sand, coral, and white clouds may reflect as much as 75%-80%. Grass and forests reflect as little as 10% of the light. The apparent "coolness" of green fields probably depends as much upon low light reflectance as it does upon any specific psychological effect of the color. The feeling of sunlight brightness balances on two factors: the amount of light falling on a surface and the amount of light reflected by that surface.

1.4.6.3 Glare at High Altitude. Glare is caused by brightness difference between various parts of a visual field. For example, an eye can be dazzled by a brighter object when adapted for a darker field of view, or view of an object is difficult due to a bright off-axis light source.

At altitudes above 40,000 ft, glare can occur from the cloud layer below the aircraft. The human facial contour is not shaped to protect from glare below the eyes as the brow does for glare above the eyes. A similar effect occurs when standing on snowy or sandy surfaces. It has been theorized that subjective haze is a persistent positive after-image of the bright cloud floor. Other causes suggest fluorescence of the crystalline lens caused by ultraviolet energy or intraocular scattering of light. While the actual cause has not clearly been established, some solutions use filters to eliminate or minimize transmitted glare light. Visor or spectacle techniques considered for below the eye reflected glare include:

a. Maximum absorption in the central portion with increasing transmission superiorly and inferiorly (gradient lenses dark on top and bottom, lighter in center)
b. Maximum absorption superiorly with increasing transmission below (gradient lenses dark on top, lightest at bottom)
c. Self-attenuating variable density filter (photosensitive lenses – increase UV, increase density)

Technique “c” would seem ideal, but in practice the dark-to-light cycling and reverse is too long to be useful in the aviation environment. Further, photosensitive lenses respond to the level of UV energy reaching the lens material. However, UV energy is largely attended by windscreens and canopies. Therefore, these lenses cannot react as intended. Techniques “a” and “b” are possible solutions. However, there is not a standardized method to produce gradient lenses that would be optimal for all airframes and aircrew positioning. These options remain available on a special order basis.

Side glare and glare from below combined with lack of light scatter at high altitude may cause a relative shadow on instrumentation. This is not a physiological condition, and the human has no adaptation for glare. Since the external environment is bright and relatively little light diffuses from outside of the cockpit, the instrument panel may appear dark as the aircrew’s attention is drawn from outside the aircraft to the panel. One solution is to use while instrument light to brighten and equalize the panel illumination with environment lighting.

It is frequently stated that lens filters reduce glare. This statement is incorrect. Glare is the result of a bright area imposing on a darker area. Typical filters reduce the overall brightness of objects by blocking portions of the energy transmission. But they don’t change the ratio of brightest and dimmest areas. Therefore, glare remains. Only polarizing filters are capable of decreasing glare. Polarizing lenses transmit wavelengths that vibrate in a particular orientation. Wavelength vibrations of other orientations are blocked, thereby reducing glare caused by off-axis light. There are limitations to use of polarizing filters in the aviation environment, however. Stress patterns in windscreens and canopies due to tempering or tension effects create polarization in those transparencies. If the orientation of the polarizing filters is perpendicular to the stress patterns, then dark bands occur and will potentially block vision.

1.4.6.4 Night Vision. There are two types of sensory receptors in the retina: rods and cones. The rods are responsible for vision under very dim illuminations (scotopic vision) and the cones for higher illuminations (photopic vision). As stated previously, cones enable color perception. This is commonly known as the “duplicity theory of vision,” in that the presence of rods and cones enables the human eye to function over an impressively wide range of lighting conditions. A common misconception is that the rods function only at night (dark conditions) and the cones function only during the day (light conditions). Actually, both rods and cones function over a wide range of light intensities, and at intermediate illumination levels they function simultaneously.

The transition zone between scotopic and photopic vision is called mesopic vision. Here both rods and cones are active, although not at peak efficiency. Mesopic vision may be of great importance to aviators, because a low level of light is present at

dawn and dusk, as well as during night operations. Under dark conditions (below moonlight intensity), cones cease to function and rods alone are responsible for vision (scotopic vision). Scotopic vision is characterized by poor visual acuity and a lack of color discrimination, but it greatly enhances sensitivity to light. Rods can function in dim light equivalent to an overcast night with no moonlight. The dimmest light cones can function is roughly equivalent to a night with 50% of a full moonlight. Another way to think of this: a white light barely seen by the rod system under scotopic conditions must increase in brightness 1,000 times to be visible to the cone system.

As discussed earlier, rods and cones are uniformly distributed through the retina. Cones are concentrated primarily in the center of the retina, while rods are primarily parafoveal and absent in the foveal (macula). Normal high resolution visual acuity is a result of the densely packed and centrally located cones located in the retina area of central vision. Therefore, under photopic conditions, the cones are functioning as intended and visual acuity is optimized in the fovea. As lighting condition reduces to mesopic, visual acuity is reduced in relation to the reduced cone function. Under scotopic conditions, cones cease to function, and, correspondingly, visual acuity is poorest. Further, under scotopic lighting, the central area of vision (cone vision) becomes a central area of no-vision (the physiologic blind spot). By eccentrically fixating (looking 17-20 deg to one side, above, or below an object), along with scanning techniques, placing the object of interest on the densest rod distribution enables rod vision to overcome the physiological blind spot. The "diamond scanning" technique involves looking above, below, and to each side of an object in a diamond-shaped scanning pattern to keep the dimly lit object from bleaching out and disappearing.

Both rods and cones undergo a chemical change when exposed to light that initiates visual impulses in the retina. The retinal photopigments regenerate to continue light detection. Under dark adaptation, the retinal photopigment cells become fully regenerated, and retinal sensitivity is at its maximum. Rods and cones differ in their rate of dark adaptation. Rods require 20-30 min (or longer) in absolute darkness to attain maximal sensitivity. Cones reach maximum sensitivity in about 5-7 min.

Rods are not sensitive to wavelengths above 650 nm (i.e., red light), while some of the cone cells are. This is the basis for use of red goggles when working in photopic illumination or red light illumination to aid in cone-based mobility. Illumination can then be high enough to enable cone function and yet still preserve dark-adapted vision.

In general, peak sensitivity of rods is 507 nm. The peak sensitivity of cones is 555 nm. If a dark-adapted person views an object, for example, a red car, under photopic conditions, the cones are fully functioning and the car will appear red. As illumination is reduced, there will be a brightness difference between the red car and its background. The red (longer wavelengths) car will appear less bright as the cones become less sensitive and rod vision becomes predominant. With further reduction of illumination the cone cells cease function and the red car will appear to lose its relative brightness and will appear as a gray car. This shift from cone vision to rod vision is called the “Purkinje shift.”

1.4.6.5 Operational Aspects of Night Vision.

Effects of altitude. Exposure to reduced oxygen at high altitude causes an increase in the adaptation time and a reduced visual performance. At 12,000 ft without supplemental oxygen (as required by current AF instructions), night vision is functioning at about 25% of its capability at sea level. For this reason, supplemental oxygen is

required from ground level and up on all tactical or combat operations. One hundred percent oxygen is not required, since the object is to maintain the blood oxygen content at an equivalent of 5,000 ft mean sea level (MSL) or lower. Therefore, the diluter on an oxygen regulator should be set in the "Normal Oxygen" setting. Note: carbon monoxide hypoxia affects vision in the same manner as high altitude. For example, 5% carbon monoxide saturation has an effect equal to hypoxia at 8,000 to 10,000 ft MSL. Smoking three cigarettes can cause carbon monoxide saturation of 4%!

Contrast discrimination. Visual acuity is reduced at night under low illumination conditions; 20/20 vision cannot be sustained at a low photopic or mesopic range. Accordingly, objects are seen at night because they are either lighter or darker than their background, in other words, contrast differences. These contrast differences may be reduced by reflected light (windscreens, visors, spectacles especially with scratched or dirty surfaces, fog, or haze). Because visual acuity and contrast detection are a function of small differences in luminance between objects and their background, any transparent medium through which the flyer must look should be spotlessly clean for night operations. Knowledge of contrast at night may be used by aircrew to detect or avoid detection by enemy observers. Pilots should fly below the enemy, if possible, then over dark areas such as land. They should fly above the enemy when over white clouds, desert, moonlight water, or snow.

Enhancing and maintaining dark adaptation. For maximum utilization of scotopic vision, 20-30 min of adaptation are required…in total darkness. A more practical alternative is to wear red-tinted goggles. Properly designed goggles (not spectacles) block all light transmission except red wavelengths. Since rod vision is not activated by the red wavelengths, the rods are able to fully regenerate, and scotopic adaptation occurs. The downsides to use of red goggles include the following: red letters on a white background may appear invisible (color confusion) and near vision may blur for pre-presbyopic or presbyopic aircrew (inadequate accommodative stimulus).

Dark adaptation develops rather slowly but can be lost in a second or two upon exposure to bright lights, either external lights (environmental, flares, afterburners, gun flashes, etc.) or bright instrument lighting. If light must be used, it should be as dim as possible and used for the shortest time possible. Dark adaptation is an independent process in each eye. Even though a bright light may shine in one eye, the other will retain its dark adaptation if protected from the light.

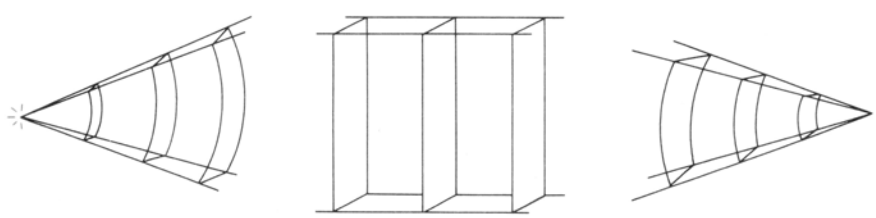
Cockpit illumination. A question often arises as to what illumination should be used in the cockpit. Red light for cockpit illumination has been used since World War II because, like red goggles, it has less of an impact on dark adaptation. However, as stated previously, it may cause reduced near vision clarity for older aircrew and there may be some color confusion. It should be also noted that night vision devices operate in a difference spectrum of wavelengths than the human eye. For example, night vision goggles (NVGs) are designed to detect infrared wavelengths, which overlap with visible red light. The result is that even very dim red light as perceived by human vision is highly visible to NVGs. White light provides a more natural visual environment without degrading the color of objects, which would enable the best visual efficiency for aircrew. But dark adaptation is sacrificed. Blue-green lighting, commonly used in modern aircraft, has several advantages. The blue-green light is near the peak wavelength sensitivity for cones, and it's easiest for accommodative focus. It is readily seen by the rod system, and it lies outside of NVG sensitivity. However, blue-green light is also more visible to enemy unaided observers than the traditional dim-red illumination. The

decision on appropriate illumination is, therefore, dependent on the visual requirements and environment in which it will be used.

1.4.6.6 Effect of Empty Visual Field. At altitude, aircrew may develop a physiological myopia secondary to ciliary muscle tone when the eye is at rest. At high altitude, one may not have a distant object on which to fixate. In such an empty visual field, reflex accommodation may occur, creating 0.50 to 2.00 diopters (focusing power) of nearsightedness (myopia). Under this condition, normal-sighted (emmatropic) or distance-vision-corrected aircrew would have reduced visual acuity at distance.

1.4.6.7 Ophthalmic Optics. Ophthalmic optics pertains to the science of refracting (bending, redirecting) light wavelengths. While the topic is primarily targeted for eye care providers and optical scientists, it has application to aviation vision. Aircrew often perform target acquisition, refueling, landing, and various other tasks through multiple optical materials: spectacles/contact lenses, visors, windscreens, ballistic/laser eye protection, etc. Distortions induced by these materials are minimized by design. But some distortions cannot be designed out or are simply an artifact of normal optical systems.

1.4.6.8 Light Characteristics. All electromagnetic energy moves or propagates, spreading light energy along a wavefront. Vergence is a description of the propagation of light. Light propagating as a parallel wavefront is called a plane or zero wave. Divergent light is a wavefront spreading out as it propagates. Conversely, a wavefront that comes together is called convergent light (Fig. 1.4.6-1).



Divergent Plane Convergent

Figure 1.4.6-1. Electromagnetic Propagation (Vergence)

1.4.6.9 Sign Convention. Whether a given wavefront is converging or diverging would seem to depend on the point of view. In the figure above, for example, the left image (labeled divergent) is diverging left to right. But it could also be described as converging right to left. To avoid ambiguity, there are certain rules, known as sign convention. This is based on Cartesian coordinates. In general, figures are drawn with light traveling left to right. All distances are drawn <u>from</u> a certain reference surface, such as a wavefront or a refracting surface, located graphically at (0,0) of an x-y graph. The x-axis extends from - to +. Distances measured to the left of the reference surface, in a direction opposite to light propagation, are considered negative. Distances to the right are considered positive. Accordingly, the radii of curvature of the above figures are measured from the wavelength toward the center of curvature. In the figure representing divergent wavefront, the radii of curvature extend to the left or negative.

The convergent wavefront radii extend to the right or in a positive direction. The measure of vergence is the inverse of the distance between the reference surface and the point the radii meet. For example, what is the vergence 2 m from a point source? $V = 1/\text{-}2M = -0.50\ M^{-1}$. M^{-1} is also called diopter. Diopters are commonly used to describe the refractive power of spectacles or contact lenses.

1.4.6.10 Refraction of Light. As light wavelengths propagate, they encounter media in their path. If the media are clear, like glass or water, the light will pass through without much loss. Clear media are also called transparent. If the light passes through a material but the medium is not transparent, it is called translucent. Examples of translucent media are frosted or milky glass. If light is unable to pass through a medium, then it is called opaque. Aircrew spectacles, windscreen, visors, sunglasses, etc. are fabricated in transparent materials.

Fermat's principle of light states: "Light takes the path that requires the least time." All laws of reflection and refraction are derived from this theorem. For example, a light wave coming from a point "A" is reflected from a mirrored surface to a point "B." The angle created by point "A" and the mirrored surface is called the angle of incidence. The angle created by point "B" and the mirrored surface is called the angle of reflection. In the case of reflection, both angles are equal. In reflection, light moves in the same media; in this example light originates and is reflected in air (Fig. 1.4.6-2).

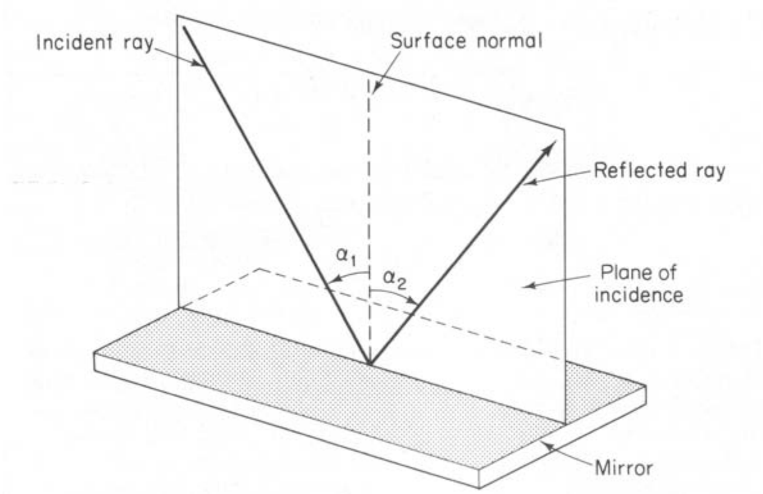


Figure 1.4.6-2. Reflected Wavelength Energy

The principle of refraction differs in that the light does not move in the same media. If there is no difference between the media, light would travel in a straight line. Refraction occurs when light passes from one medium that has a given density (index of refraction) to a different density. For example, originating in air and passing through glass, the path of a light wave is no longer straight. It is refracted. Snell's law of refraction states that light passing from a lower index (density) to a higher more dense index is bent toward the surface normal (Fig. 1.4.6-3). If the light travels in the more to less dense medium, it is bent away from the surface normal. One example of this effect is when viewing fish swimming in water. The actual location of the fish is displaced from the visually perceived location if the observer is viewing out of the water.

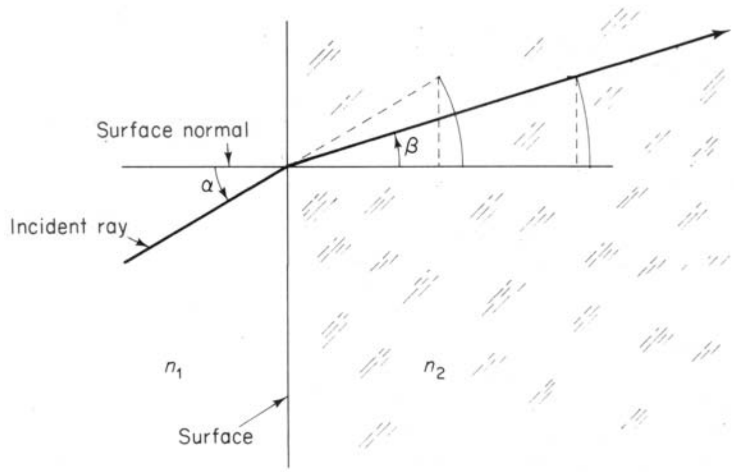


Figure 1.4.6-3. Refraction of Wavelength Energy

The point of this description is to provide a simple concept of refraction that occurs in any situation in which light passes through a given medium to a more or less dense medium. This phenomenon gives rise to many visual misperceptions. A visor or windscreen may cause an errant location of a target if the medium is not uniform in density or curvature. Changes in air density give rise to the appearance of wavy lines above a heated surface, such as tarmac or a desert.

1.4.7. Visual Illusions and Problems

Spatial disorientation may arise from labyrinthine, proprioceptive, or visual mechanisms. This section will only address those illusions associated primarily with visual perception. There are two forms of visual processing: foveal (central, focal) and peripheral (ambient). Foveal vision is mainly concerned with object recognition, whereas peripheral vision deals mainly with spatial orientation.

The visual perception of something existing objectively but misinterpreted is a visual illusion. In a study by Bell and Chunn (1964), spatial disorientation and visual restrictions were the psychological factors responsible for approximately 23% of the aircraft accidents they investigated. Visual illusions and reduced vision may cause judgment errors that cannot be compensated for by corrective actions. For example, landing at night under inclement weather presents reduced visual situations for a pilot. The poor visual cues complicate distance judgments, making time for corrective actions limited.

The visual system has to make sense of the world in which everyday objects are distorted by perspective. Visual interpretation of two distant illuminated objects can lead to the perception that one is closer than the other when they may be equally distant but differ in brightness. Obviously a large portion of our perceptual experience is based on real world observations. For the aviator, these learned perceptions can lead to visual illusions. One important phenomenom is the apparent unchanged size of a perceived image of an object as its distance from the observer changes. The retinal image reduces in size as the observer moves further from the object; the mental image does not change proportionally. This is the perceptual phenomenom of size constancy. Related to this is the perception of depth. Retinal displacement (disparity) of images on the observer’s two eyes gives rise to stereoscopic (binocular) depth perception.

Aircraft windscreens, visors, and other transparencies can cause refraction, magnification, and distortion of images. Debris, heavy rain, spectacle tints, and such can reduce vision sufficient to make objects like power lines, flag poles, trees, and other aircraft invisible. Further, distance judgment may be reduced as ground lighting may appear less intense, thereby giving the illusion of greater distance. Depth perception arises from monocular and binocular cues.

Monocular cues (single-eye perception) include:

a. Size of the retinal image (size constancy) – judgment is based on known and/or comparative object sizes.
b. Motion parallax – the relative motion of images across the retina. Objects nearer than a fixation point move against observer's motion. Further objects move in the same direction.
c. Interposition – one object is obscured by another.
d. Texture or gradient – detail is lost with increasing distance.
e. Linear perspective – parallel lines converge at a distance.
f. Apparent foreshortening – a circle appears as an ellipse at an angle.
g. Illumination perspective – light sources are assumed to come from above.
h. Aerial perspective – distance objects appear more bluish and hazy.

Binocular cues (two-eye perception) are vergence and accommodation, useful for near distances and stereopsis (up to 200 yd). Binocular cues occur due to disparate retinal images sufficient to give rise to stereopsis but not to the level to cause diplopia (double vision).

Common aviation visual illusions are runway aerial perspective, visual autokinesis, linear and angular vection, black hole approach, sloping cloud decks, and lean-on-the-sun illusion.

1.4.7.1 Runway Aerial Perspective. Visual orientation during runway landing is based in part on learn perception. Repetition of aircraft landing on a given runway develops perception of the relative size (length, width) of the runway at various time intervals of successful attempts. The skill developed is essential to a pilot's performance. However, variation from a highly practiced runway landing requires adaptation to relatively subtle changes. A runway that is sloped upwards 3 deg will give the illusion that the runway is narrower than expected and, therefore, the aircraft is too high on the approach. If the pilot corrects the aircraft altitude to match the visual perception, the glide slope will be shallower than planned, resulting in a short or hard landing. The opposite will occur on a downward-sloping runway. A runway narrower or longer than expected will likewise give the visual perception of a too high approach.

At night, the pilot attends to the runway lights for visual confirmation of his/her aircraft's approach. If the runway lights are displaced laterally, a similar misperception will occur as described above. The terrain near the runway may also give false impression of height as well. If the terrain at the approach end is descending, the pilot may fly too shallow. If the terrain is sloping up to the runway, the pilot may approach steeper than required.

Other hazardous runway illusions that may give false height perception may be produced by the presence of snow, fog, smooth water nearby, size of buildings, size of vegetation, and differences in runway light brightness.

1.4.7.2 Visual Autokinesis. The apparent wandering of an object or a light when viewed against a visually unstructured background is called autokinesis. A bright star may be seen as moving in a circle or moving linearly. For example, during a night formation flight, only one running light of the lead aircraft is seen; other pilots may have difficulty in distinguishing real movements of the aircraft. The exact cause is unknown, but it may be related to normal subconscious eye movements. To counter this illusion, avoid staring (fixating) at solitary lights for more than a few seconds and establish a reliable reference in the aircraft such as the canopy border. Look at Figure 1.4.7-1. Note that the image at the point of your attention has no perception of motion, while other portions appear to have motion.

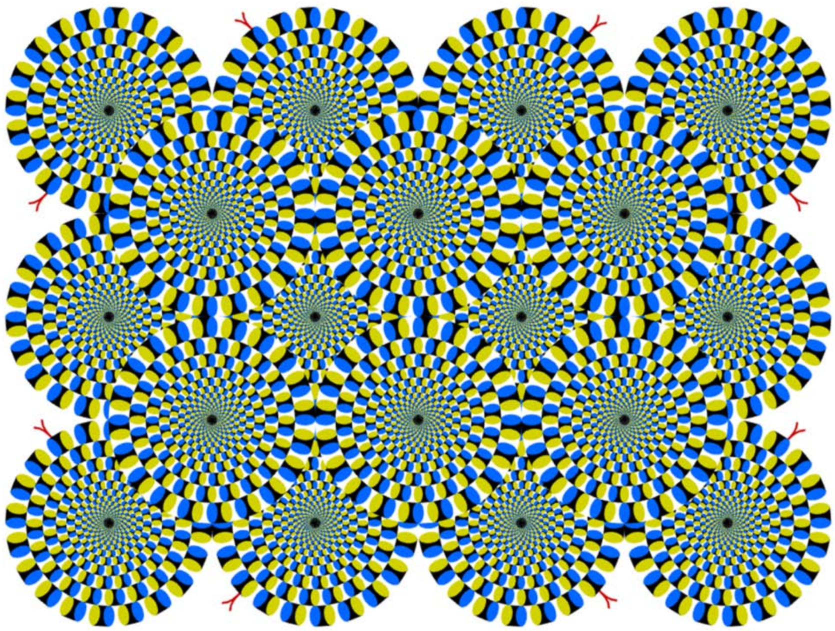


Figure 1.4.7-1. Autokinesis

1.4.7.3 Linear and Angular Vection. If a large structure nearby moves forward, there is an illusion that one is slipping backward. The most familiar situation occurs when one is stopped at a traffic light and a nearby car rolls forward. The perception is created that your vehicle is rolling backward.

1.4.7.4 Black Hole Approach. The black hole illusion is produced during night landing, when there are no visual references except runway lights. The situation may worsen when the lights of a city near the end of the runway make the approach appear high (no distinct horizon). To make the perception match expectation, the pilot lowers the aircraft and lands short. A similar situation is produced by blowing snow or sand and also when the runway and nearby terrain are covered by fresh snow or sand.

1.4.7.5 Sloping Cloud Decks. A sloping cloud deck may cause the pilot to adjust the aircraft attitude to what is perceived as the real horizon. This is particularly hazardous when flying near mountainous terrain. There is a strong tendency to accept the level appearance of the clouds as the true horizon, especially if it is indistinct. An unperceived angle of bank will lead to altitude loss, if not corrected.

1.4.7.6 Lean-on-the-Sun Illusion. Terrestrial-based observers are accustomed to seeing the brighter part of the horizon above and the darker ground below. When flying in weather, an attempt to position the brighter cloud layer above may result in an unexpected aircraft attitude. When flying in and out of cloud layers, the pilot generally will remember the relative bearing of the sun before the weather was encountered. This causes the pilot to unconsciously seek the "correct" visual image, resulting in imprecise flight. Formation flight under these conditions can be hazardous.

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Concepts

Dark adaptation
Diamond scanning
Visual acuity

Vocabulary

Cone cells
Crystalline lens
Foveal vision
Night vision goggles (NVGS)
Peripheral vision
Photopic vision
Presbyopia
Retina
Rod cells
Scotopic vision

1.5. Hearing and Noise

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1.5.1. Introduction

The human auditory system is the sensory system that makes humans feel most “present” in their environment and allows them to communicate easily with other persons. It can accommodate a very wide range of sound levels, from 0 dB, the threshold of hearing, to 130 dB, the threshold of auditory pain. However, at the higher sound pressure levels, the auditory system can suffer temporary and/or permanent damage, resulting from years of overexposure and occasionally from a single exposure. This chapter will provide the basic information about sound and noise; how they relate to your sense of hearing, including the performance of the human auditory system; and how to protect hearing in continuous and impulsive military noise environments.

Hearing loss is prevalent among military personnel. High levels of noise, long duration exposures, and, all too frequently, the improper use of hearing protectors result in large amounts of hearing loss. Annual disability payments by the Department of Veterans Affairs (VA) for hearing loss as primary disability have been growing over the past three decades. For example, Figure 1.5.1-1 shows the rapid increase in hearing loss compensation payments for 1977-2006. These figures do not consider the treatment or retraining costs. The total cost in 2006 for hearing loss compensation, treatment, and retraining was estimated to be over $3B. Moreover, high noise levels and hearing loss frequently degrade voice communication capability, which has a negative impact on mission effectiveness and safety.

Figure 1.5.1-1. VA Hearing Loss Disability Payment Annual Costs

1.5.2. Physics of Noise

Noise is undesired or unwanted sound. Sound or noise is usually described quantified in units of decibels (dB). Decibels are not an absolute measure but a ratio of the measured sound pressure to a reference sound pressure. The most common reference is:

$$0 \text{ dB} = 20\ \mu\text{Pa} = 2 \text{ X } 10^{-5} \text{ Pa}$$

Decibels in sound pressure level (dB SPL) relate an absolute measure of pressure (Pascals) to the reference pressure. Decibels for hearing function (dB HL – hearing level or dB HTL – hearing threshold level) are expressed relative to the average thresholds for persons with normal hearing. At 1 kHz, 0 dB HL is the quietest sound that can be heard by an average person with normal hearing; it also corresponds with 0 dB SPL. However, as the frequency gets lower than 1 kHz or higher than 4 kHz, 0 dB HL will correspond to increasingly higher absolute pressures and higher sound pressure levels.

People are less sensitive to sound/noise at lower frequencies and more sensitive in the middle and higher frequencies. The A-weighting function shown in Figure 1.5.2-1 is used in the United States for assessments of hearing damage risk in the workplace and for environmental noise assessments. Currently, it is the best predictor of potential hearing loss in the workplace and of potential annoyance in the community. The C-weighting function is the second most often used weighting function and, in reality, is the only other weighting function that is commonly used. Sound level meters typically have both the A-weighting and C-weighting function. Measuring the overall C-weighted noise level and subtracting the overall A-weighted noise level give an indication of the amount of low frequency noise in the spectrum. A positive difference (C-A) indicates more low frequency spectral content. This information can be very useful when selecting hearing protection for a particular noise.

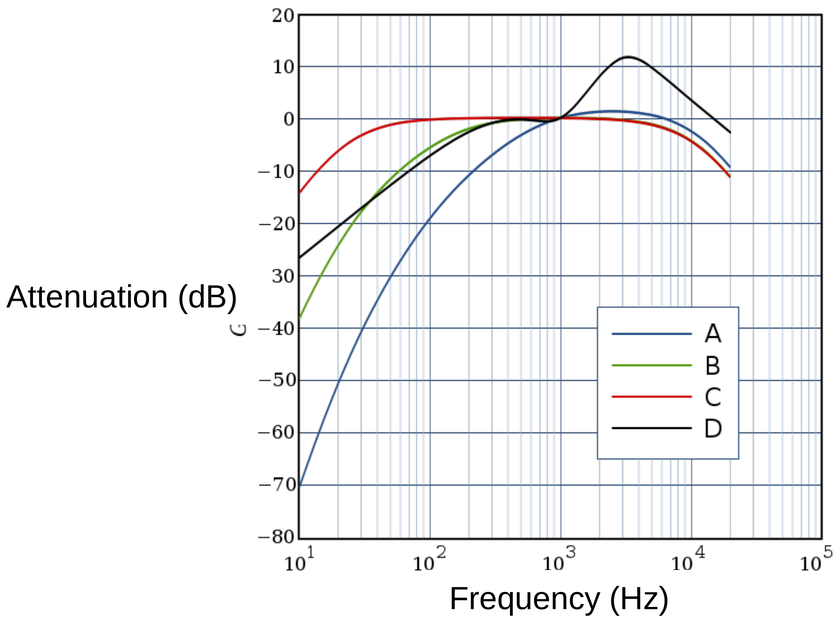


Figure 1.5.2-1. Weighting Functions, A, B, C, and D

Sound/noise is measured on a logarithmic scale. In engineering terms, a doubling of the sound energy results in a 3 dB increase in the sound level. In humans a doubling of the perceived loudness is approximately a 10-dB increase in sound level. For an average untrained person, a just noticeable change in sound level is a 3-dB change, and a trained listener can discriminate sound level changes as small as 1 dB.

Humans with good hearing can "hear" an extremely large range of sound pressures. The faintest sound humans can hear is about 0 dB or 20 µPa or 0.002 dynes/cm^2. Table 1.5.2-1 shows the relationship between pressure and sound pressure decibels (in air) relative to the standard reference level for 0 dB (0.0002 dynes/cm^2). The pressures have a very large range. By calculating the logarithm of the pressure ratio (the ratio of the pressure relative to 0.002 dynes/cm^2) and multiplying the result by 20, the decibel level can be calculated.

$$decibels = 10 \times \log_{10}\left(\frac{pressure}{0.0002\,dynes/cm^2}\right)^2 = 20 \times \log_{10}\left(\frac{pressure}{0.0002\,dynes/cm^2}\right)$$

Since decibels are based on the logarithm of the pressure ratios, we say that decibels are a logarithmic function. When adding sound pressure levels, logarithmic addition needs to be performed. For example, 93 dB + 93 dB = 96 dB (this also is an example of the 3-dB-per-doubling rule), and 93 dB + 83 dB = 93.4 dB. The equation below shows how to perform logarithmic addition of sound pressure levels.

$$sum\,SPLdecibels = 10^{SPLdB1/10} + 10^{SPLdB2/10}$$

Table 1.5.2-1. Decibels and Corresponding Pressures in dynes/cm^2 and Pascals

Decibels (dB)	Pressure (dynes/cm^2)	Pressure (Pa)
0	0.0002	0.00002
10	0.001	0.0006
20	0.002	0.0020
30	0.006	0.0006
40	0.020	0.002
50	0.063	0.006
60	0.200	0.02
70	0.632	0.06
80	2.00	0.2
90	6.23	0.6
100	20.00	2
110	63.25	6
120	200.00	20
130	632.46	63
140	2000.00	200
150	6324.56	632

1.5.3. Noise Exposure Criteria

Noise exposure criteria for the U.S. military and Department of Defense (DoD) civilians are described in DoD instructions, military standards, and military instructions. The Army, Navy, and Air Force have separate instructions and hearing conversation programs. However, the noise exposure criteria are described separately for continuous noise (noise with a duration longer than 1 s) and impulsive noise (noise with a rapidly (<50 ms) rising peak and a duration less than 1 s). The noise exposure criteria have been developed based on long-term hearing loss studies from a wide range of exposures.

Generally, noise exposure criteria are a matter of policy. Technical experts can predict the amount of permanent hearing loss or NIPTS (noise-induced permanent threshold shift) in a population from years of exposure to noise within given criteria. Generally, noise exposure criteria are a balance between acceptable levels of hearing loss and the noise exposure levels in the criteria. One example from the 1998 National Institute for Occupational Safety and Health (NIOSH) Criteria Document is shown below in Table 1.5.3-1.

Table 1.5.3-1. Estimated Excess Risk of Incurring Material Hearing Impairment[a] as a Function of Average Daily Noise Exposure Over a 40-Year Working Lifetime[b]

Reporting Organization	Average Daily Noise Exposure [dB(A)]	Excess Risk (%)[c]
ISO[d]	90	21
	85	10
	80	0
EPA[e]	90	22
	85	12
	80	5
NIOSH	90	29
	85	15
	80	3

[a]For purposes of comparison in this table, material hearing impairment is defined as an average of the HTLs for both ears at 500, 1000, and 2000 Hz that exceeds 25 dB.
[b]Adapted from 39 Fed. Reg 43802(1974b).
[c]Percentage with material hearing impairment in an occupational-noise-exposed population after subtracting the percentage who would normally incur such impairment from other causes in an unexposed population.
[d]International Standards Organization.
[e]Environmental Protection Agency.

1.5.4. Continuous Noise Criteria

DoD Instruction 6055.12 specifies the noise exposure criterion for continuous noise at 85 dB(A) level equivalent (L_{eq}) or 8-hr TWA (time weighted average) with a 3-dB/doubling exchange rate. This criterion brings two important factors. First, the exposure is a combination of the noise level AND the exposure time. Second, for every 3-dB increase in exposure level, the allowable exposure time is reduced by a factor of two. Additionally, the DoD instruction exposure criterion is more protective, i.e., allows

less noise exposure, than the Occupational Safety and Health Administration (OSHA) 90-dB(A) criterion 8-hr TWA and a 5-dB/doubling exchange rate (which applies to DoD contract personnel and other U.S. industrial personnel). Table 1.5.4-1 shows the allowable exposure times in a 24-hour period for a wide range of A-weighted noise levels using the DoD criterion. For exposure times greater than 8 hours, the recovery time at less than 75 dB(A) should be equal to or greater than the exposure time.

Noise levels at the ear can be computed by subtracting the hearing protection level from the ambient noise level. Double hearing protection is usually recommended for levels above 115 dB(A). A nonauditory, whole body noise exposure limit has been established at 150 dB overall sound pressure level or 145 dB in any single 1/3 octave or octave band. This whole body limit was established empirically by a group of scientists who exposed themselves to high level whole body noise from 130 dB to approximately 170 dB and reported their findings. Since there were no unusual symptoms at or below 150 dB, the limit was established and has been reaffirmed on several occasions by teams measuring the near-field noise of high performance jet aircraft.

Table 1.5.4-1. Allowable Noise Levels at the Ear and Times in a 24-hr Period with Equal Rest at ≤ 75 dB(A)

A-Weighted Level [dB(A)]	Allowable Exposure Time (hr)	Allowable Exposure Time (min)	Allowable Exposure Time (s)
80.2	24	1442	86502
82	16	960	57600
85	8	480	28800
88	4	240	14400
91	2	120	7200
94	1	60	3600
97	0.5	30	1800
100	0.25	15	900
103	0.125	7.5	450
106	0.0625	3.75	225
109	0.0313	1.875	112.5
112	0.0156	0.938	56.25
115	0.0078	0.469	28.13
118	0.0039	0.234	14.06
121	0.0020	0.117	7.03
124	0.0010	0.059	3.52
127	0.0005	0.029	1.76
130	0.0002	0.015	0.88

Figure 1.5.4-1 shows some of the worst-case near-field noise levels from high performance fighter aircraft. The levels range from 135 dB to 148 dB at military power and from 146 dB to 153 dB at afterburner power.

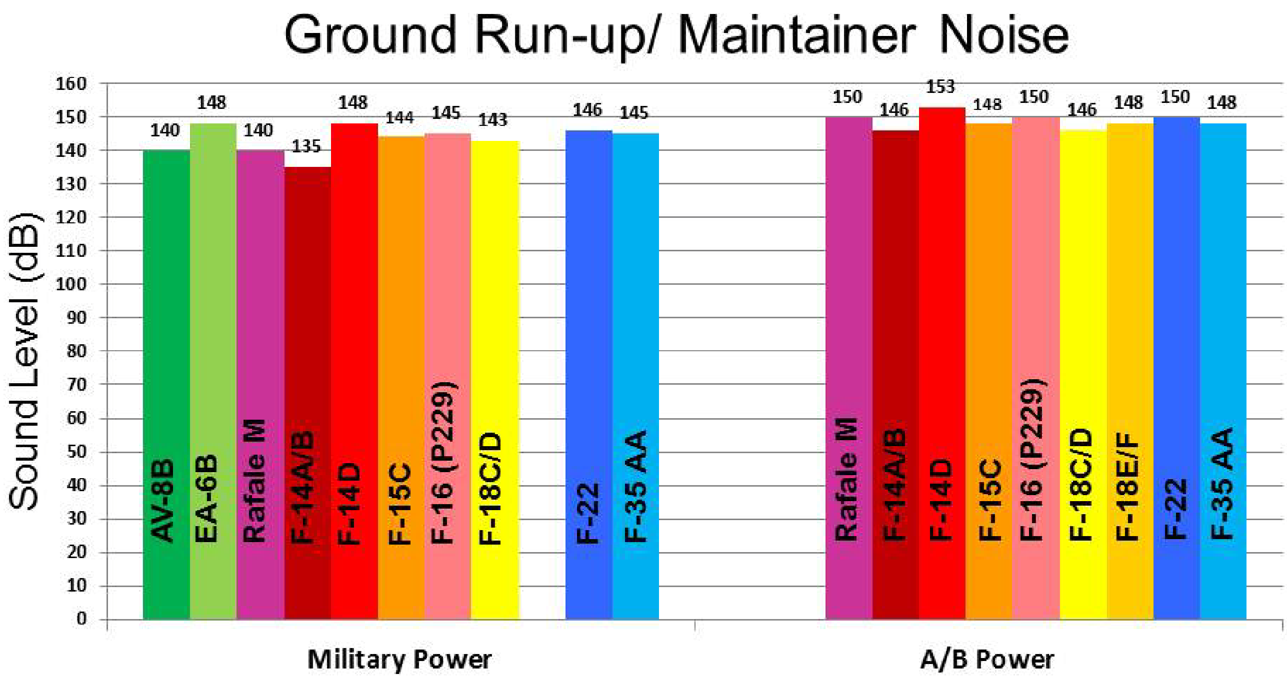


Figure 1.5.4-1. Worst-Case Near-Field Noise Levels From High Performance Fighter Aircraft

1.5.5. Impulsive Noise Criteria

Impulsive noise generally results from the firing of a weapon, small arms to artillery; mortars; or explosions (improvised explosive devices (IEDs), detonation cord – emergency egress or ejection – canopy cutting). The levels are usually much higher than continuous noise and also of a much shorter duration. Some typical levels are shown in Table 1.5.5-1.

The impulsive noise exposure criterion is currently Military Standard (Mil Std) 1474D as shown in Figure 1.5.5-1. This standard was developed primarily for small arms fire and has been shown to overestimate the hearing damage risk for artillery and blasts. A 30+ year debate has raged in the scientific community regarding exposure criteria for impulsive noise. The problems seem to be the multiple damage mechanisms and the wide range of levels and durations. Several other criteria have been proposed, but none between the number of impulses and level that describe standard methods for measuring impulsive noise. Additionally, for impulses above 195 dB, blast lung or other soft tissue injury should be considered.

Table 1.5.5-1. Typical Impulsive Noise Levels from Weapons Fire

Model	Name	Location	Sound Level (dB)(peak)
M16A2	5.56mm rifle	Shooter	157
M9	9mm pistol	Shooter	157
M249	5.56mm squad automatic weapon (SAW) fired from a HMMWV	Gunner	159.5
M60	7.62mm machine gun fired from a HMMWV	Gunner	155
M2	0.50 caliber machine gun fired from a HMMWV	Gunner	153
MK 19 Mod 3	Machine gun fired from a HMMWV	Gunner	145
M26	Grenade	At 50 ft	164.3
M3	MAAWS recoilless rifle	Gunner	190
M72A3	Light antitank weapon (LAW)	Gunner	182
M119	105mm towed howitzer at charge 8	Gunner	183
M198	155mm towed howitzer firing M203 propellant	Gunner	178
M109A5/6	Paladin, 155mm self- propelled howitzer firing M4A2 zone 7 charge	In fighting compartment, hatches open except driver's	166.1
M110A2	8-in. self-propelled howitzer firing M106 projectile with a M188A1 zone 9 propelling charge	Gunner	176.9

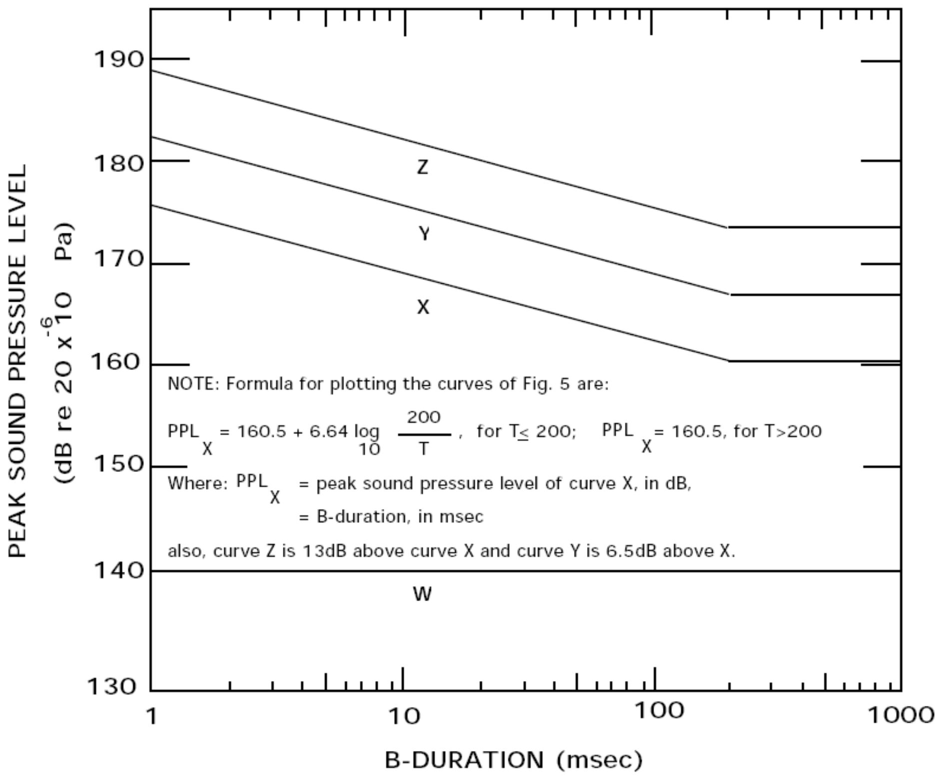


Figure 1.5.5-1. Mil Std 1474D Impulsive Noise Exposure Criteria

1.5.6. Noise Dose Calculation Method for Continuous Noise

Noise dose is a combination of noise level and duration evaluated relative to a noise exposure criterion and exchange rate. The goal for noise-exposed workers is to keep the noise dose to 100% or lower on a daily basis. Noise dose can also be computed/calculated for time durations longer or shorter than a standard 8-hr work day. An example would be the noise dose accumulated by a pilot during a given flight in the high noise of the cockpit. The flight might be only 1.5 hr in duration, but the associated noise dose could easily exceed 100%. Another example would be the noise dose accumulated in command and control centers where the noise is at a relatively lower intensity but the duration may be significantly greater than 8 hr. Once again the allowable noise dose could easily exceed 100%. Noise dose is an aggregate or summation of several individual noise doses calculated from noise spectra/levels and times at each noise level evaluated relative to the noise exposure criterion.

The equation below gives a method for calculating noise dose from n, multiple events for any noise exposure criterion, and exchange rate.

$$Dose = 100 \times \sum_{i=1}^{n} \frac{t_i \times 2^{\left(\frac{L_i - L}{E}\right)}}{T}$$

Where:

Dose = percentage dose
t_i = exposure time in minutes for the i^{th} time period
L_i = A-weighted level in dB(A) for the i^{th} time period
L = exposure criterion A-weighted level in dB(A) [e.g., 85 dB(A)]
E = exposure criterion exchange rate in dB per doubling of exposure time (e.g., 3 dB/doubling)
T = exposure criterion time in minutes (e.g., 8 hr would be 480 min)
N = total number of exposure time periods (e.g., if you had 17 separate noise levels and time periods, then n=17)

Below are two examples of detailed equations. The first example, on the left, is for a noise exposure criterion of 85 dB(A), for 8 hr (480 min), with a 3-dB-per-doubling exchange rate. The second example, on the right, is for a noise exposure criterion of 90 dB(A), for 8 hr (480 min), with a 5-dB-per-doubling exchange rate.

$$Dose = 100 \times \sum_{i=1}^{n} \frac{t_i \times 2^{\left(\frac{L_i - 85}{3}\right)}}{480}$$

$$Dose = 100 \times \sum_{i=1}^{n} \frac{t_i \times 2^{\left(\frac{L_i - 90}{5}\right)}}{480}$$

Included below are the equations in MS Excel™ where A2 is the time in minutes, B2 is the exposure level in dB(A), and 8 hr is represented as 480 min.

= 100*((A2*2^((B2-85)/3))/480)
DoD Criterion (85/8/3)

= 100*((A2*2^((B2-90)/5))/480)
OSHA Criterion (90/8/5)

Tables 1.5.6-1 and 1.5.6-2 show the spreadsheet cells used to calculate the noise dose in the preceding examples. The first table is for the DoD 85-dB(A), 8-hr, 3-dB/doubling criteria while the second table is for the OSHA 90-dB(A), 8-hr, 5-dB/doubling criteria.

Table 1.5.6-1. DoD Criterion (85/8/3)

	A	**B**	**C**
1	**Time (min)**	**Level [dB(A)]**	**Dose (%)**
2	A2	B2	=100*((A2*2^((B2-**85**)/**3**))/480)
3	A3	B3	=100*((A3*2^((B3-**85**)/**3**))/480)
4	A4	B4	=100*((A4*2^((B4-**85**)/**3**))/480)
5		**Total Dose**	=Sum(C2:C4)

Table 1.5.6-2. OSHA Criterion (90/8/5)

	A Time (min)	B Level [dB(A)]	C Dose (%)
1	Time (min)	Level [dB(A)]	Dose (%)
2	A2	B2	=100*((A2*2^((B2-90)/5))/480)
3	A3	B3	=100*((A3*2^((B3-90)/5))/480)
4	A4	B4	=100*((A4*2^((B4-90)/5))/480)
5		**Total Dose**	=Sum(C2:C4)

Next are two examples of the dose calculation using each sample noise exposure criterion.

First, we will calculate the dose for the following exposure. A person is exposed to 85 dB(A) at the ear for 4 hr, 88 dB(A) for 1 r, and 91 dB(A) for 30 min.

The example dose calculations for the two exposure criteria are as follows: first, on the left of Table 1.5.6-3, the 85-dB(A)-with-3-dB/doubling criterion; second, on the right, the 90-dB(A)-with-5-dB/doubling criterion.

Table 1.5.6-3. First Example of Dose Calculations

85 dB(A)/8 hr/3 dB			90 dB(A)/8 hr/5 dB		
Time (min)	**Level [dB(A)]**	**Dose (%)**	**Time (min)**	**Level [dB(A)]**	**Dose (%)**
240	85	50	240	85	25
60	88	25	60	88	9
30	91	25	30	91	7
Total		100			41

For the second example, we will calculate the dose for a different exposure. This time, a person is exposed to 95 dB(A) at the ear for 1 hr, 90 dB(A) for 2 hr, and 85 dB(A) for 4 hr (Table 1.5.6-4).

The dose calculations for the two exposure criteria are as follows: first, on the left, the 85-dB(A)-with-3-dB/doubling criterion; and second, on the right, the 90-dB(A)-with- 5-dB/doubling criterion.

Table 1.5.6-4. Second Example of Dose Calculations

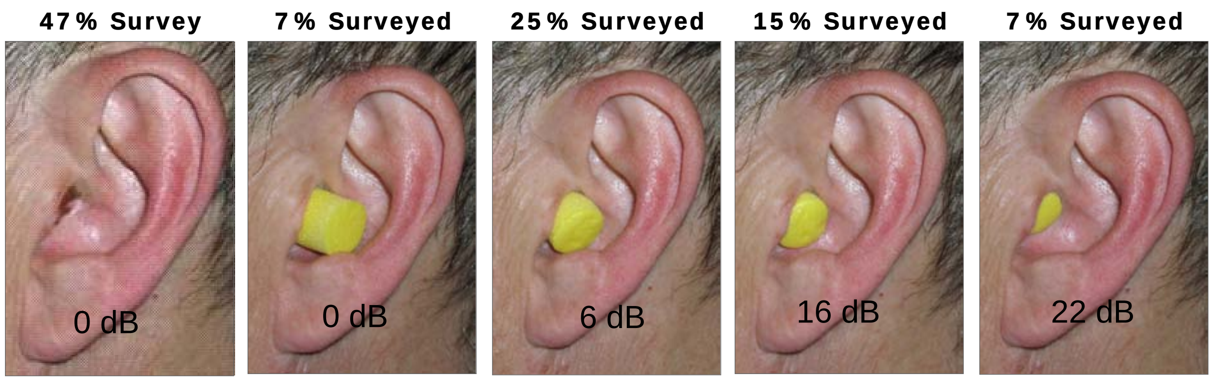
85 dB(A)/8 hr/3 dB			90 dB(A)/8 hr/5 dB		
Time (min)	**Level [dB(A)]**	**Dose (%)**	**Time (min)**	**Level [dB(A)]**	**Dose (%)**
60	95	126	60	95	25
120	90	79	120	90	25
240	85	50	240	85	25
Total		255			75

As can be seen, the exposure criterion has a dramatic effect on the total dose. The examples and spreadsheets can be expanded/extended to add as many different noise exposure levels and time as desired for the calculation of the total noise dose. Once the noise dose is calculated for each level and time, all the noise doses are then summed to calculate the total noise dose.

1.5.7. Hearing Protection

Hearing protection technologies can be very simple (foam earplugs or simple earmuffs) to very complicated (active noise reduction earplugs with large volume earmuffs mounted in a special helmet to reduce bone conduction). The major factor in the effectiveness of a hearing protector is compliance. Is it worn and worn well? Frequently, the high noise exposure for an industrial worker is the 30 minutes at lunch when he or she is not wearing the hearing protector.

A recent survey of U.S. Navy flight deck crews found a startling fact. Most of the personnel were not getting anything close to the attenuation the recommended earmuffs and earplugs provided because almost half of the users were not wearing the earplugs and many of the rest were not wearing them properly. The data from the Navy study are shown in Figure 1.5.7-1. Since the attenuation data are mean minus two standard deviations, for each group 98% of the personnel in the applicable group received the attenuation value shown or better.



Attenuation data from U.S. Air Force Research Laboratory ANSI S12.6-1997 (R2002) Method A (Experimenter Supervised/Verbally Coached) Testing (mean minus two standard deviations)

Figure 1.5.7-1. Percentage of Earplug Insertion Depth and Estimated Attenuation (Naval Air Systems Command Survey of 301 Flight Deck Personnel)

Typical laboratory performance of earplugs ranges from 10 to 30 dB with about 33% of the laboratory value being realized in a well-motivated using population. Typical laboratory performance of earmuffs or helmets ranges from 10 to 25 dB with about 90% laboratory value being realized in a well-motivated using population. Combination hearing protection of earmuffs and earplugs used together typically results in total attenuations of about 5 dB greater than the better performing hearing protector. Additional consideration also needs to be given to flanking pathways such as bone conduction once the attenuation of the hearing protector achieves 40-45 dB.

Active noise reduction (ANR) earmuffs typically provide 10-15 dB additional protection in the frequency range from 125 Hz to 800 Hz and, therefore, have the most dramatic effect in low-frequency-dominated noises such as propeller aircraft, helicopters, tanks, etc. However, in many jet aircraft, the noise exposure is driven by the low-frequency noise, and ANR earmuff systems can also be effective in these environments. Noise exposure calculations should be conducted with total mission scenarios – noise levels and times for each mission segment summed for the total mission.

Active noise reduction earplugs are just emerging but can provide 5-12 dB of additional protection in the frequency range from 125 Hz to 3 kHz. These systems have been originally developed for maintainers working in the very high noise levels found in the near-field of a high-performance jet. These systems initially were very expensive but were expected to decrease in cost with higher production quantities.

Tactical hearing protection systems generally have been designed to attenuate both impulse noise and continuous noise while providing some ambient listening capability and enhancing communication capability with interfaces to radio communication. These devices mostly are electronic earplugs or electronic earmuffs, although a few passive earplugs and passive earmuffs are available.

1.5.8. Sense of Hearing

The human sense of hearing has many functions, including auditory detection, identification, localization, and speech communication. Auditory detection thresholds are determined by the ambient noise environment, which may or may not mask the event, and the hearing threshold of the listener. A 10-dB temporary threshold shift or TTS can reduce the detection threshold such that the event or possible threat is much closer (i.e., an event that would have been detected at 100 ft prior to the TTS would be detected at 31 ft after the 10-dB TTS). Clearly, a TTS can have a significant effect on auditory detection thresholds. Identification thresholds and speech communication effectiveness can be similarly affected.

Auditory localization allows a listener to determine the location of a sound source. Most people can localize a sound source within a few degrees. The auditory system seems to be integrated with the visual system and can very quickly and effectively direct the gaze of the eye to particular locations. The effect of localization cues on visual search is shown in Figure 1.5.8-1. These localization cues are moderately disrupted by passive hearing protectors such as earmuffs and earplugs, but in situations where there is time (1-2 s) and head motion is allowed, the disruptive effects are not large. However, in situations where double hearing protection is used, the localization cues seem to be completely disrupted, and the listeners cannot reasonably localize. The tactical hearing protection systems previously described have been designed to restore or preserve these localization cues.

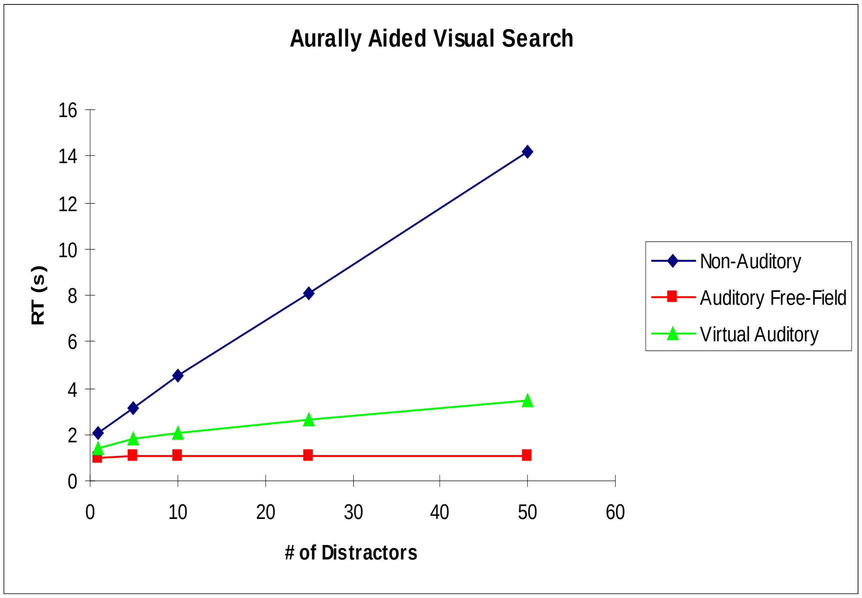


Figure 1.5.8-1. Effect of Auditory Localization Cues on Visual Search with Distracters

Speech communication in noise is primarily dependent on the speech-to-noise ratio (SNR). The higher the SNR (up to 30 dB), the better the speech intelligibility. However, in military communication systems, speech intelligibility cannot be accurately predicted from SNR due to nonlinearities in the communication system. Speech intelligibility tests such as the Modified Rhyme Test (MRT) and the Diagnostic Rhyme Test (DRT) have been shown to be effective measures of speech intelligibility performance over communication systems and have been described in an American National Standards Institute (ANSI) standard, S3.2-2009.

1.5.9. Summary

The auditory system is a robust communication pathway critical to the well being of the listener. The auditory system provides communication capability, detection, identification, and localization capability for threats and targets and works with the visual system to identify locations of interest. The very wide range of the auditory system also makes it susceptible to damage at higher noise levels, and it must be protected by either restricting the exposure level and time or by providing hearing protection, or by doing both. Once lost, hearing cannot be restored. Hearing loss due to military noise exposures not only affects operational readiness but the personal lives of those affected. Hearing loss should be considered in the same class as progressive blindness. Glasses or lenses filter light but do not restore vision. Likewise, hearing aids do not restore hearing when the sensory cells are permanently damaged.

References

ANSI S3.2-2009 American National Standard Method for Measuring the Intelligibility of Speech Over Communication Systems

DoD Instruction 6055.12, March 5, 2004, DoD Hearing Conservation Program (HCP)

NIOSH "Criteria for a Recommended Standard for Occupation Noise Exposure" (1998) Dept. Health and Human Services, Centers for Diseases Control and Prevention, National Institute for Occupational Saefty and Health Pub. No. 98-126.

Recommended Readings

Bjorn, et al. U.S. Navy Flight Deck Hearing Protection Use Trends: Survey Results, NATO RTO MP-HFM-123-P-01, 2005

McKinley, et al, Improved Hearing Protection for Aviation Personnel, NATO RTO MP-HFM-123-P-13, 2005

NATO RTO HFM TG-147 Final Report Hearing Protection - Needs, Technologies, and Performance. 2009

Concepts

Noise dose
Noise exposure criteria

Vocabulary

Decibels (dB)
Impulsive noise
Noise

1.6. Exercise and Nutrition

1.6.1. Physical Activity, Exercise and Physical Fitness

Neal Baumgartner, Maj, USAF (ret), Ph.D.

The dim glow of red cabin lights reflects off each of their faces… at the 2-min warning the team is on their feet, shuffling toward the open ramp, each saddled with over 80 lb of gear, jumpmaster making the final checks. The light goes green and the mass of bodies moves quickly to the door. For the last 2 hr, each one has been propped against the hull of the fuselage balanced on the web seating and trying to stay limber. Up until now, it's been mental preparation: insertion to the LZ, deployment to the objective, preparation for recovery…check, double-checks. Now the moment of truth: heart pounding, muscles straining against the mass of equipment harnessed head to foot; like pack mules each one steps to the ramp and out into the darkness. Now begins the complex ballet of muscles and tendons holding body position, maintaining control during freefall…no sudden moves, subtle adjustments only. Prepare to land: new muscle activity and mental preparation to gather together equipment and get ready to move to the objective. The event relies upon the principles of total body fitness: muscle movement, stamina, and endurance. Developing proactive and purposeful activities is the focus of this chapter and the core of success in every dynamic arena in the Air Force.

1.6.2. Physical Fitness Training Principles

1.6.2.1 Introduction. It is inherent that aircrew establish and maintain a consistent state of physical fitness for both health and performance. A comprehensive aircrew functional physical fitness program must follow fundamental exercise principles and exercise program design and planning. The program should include: (1) primary physical fitness components of cardiorespiratory endurance, body composition, muscular strength, muscular endurance, flexibility-stability-mobility, and as applicable (2) skill-based physical fitness components of agility, balance, coordination, power, reaction time, and speed. A program of deliberately designed multiyear to weekly training cycles should encompass progressively applied physical training. Within these cycles a daily general exercise pattern should address primary workout phases of movement preparation, cardiorespiratory endurance, muscle fitness across the prioritized physical movement patterns, combination fitness, skills training, and movement transition-cessation. Finally, the training should include lessons on body composition, injury prevention and treatment, and fitness testing and standards. Accomplished in the above manner, this functional fitness program will ensure aircrew are prepared for the physical challenges of combat operations as well as stress the vital importance of maintaining physical fitness throughout one's career.

1.6.2.2 Reasons to Exercise. Exercise is a powerful medicine quite unlike any pill available, and it's a health-saving nostrum that brings intoxicating benefits with few side effects. It can lengthen the span and quality of life, decrease the risk of several diseases, and alleviate mental anxiety and depression as well as enhance human

performance in athletic and occupational arenas. However, time and effort to perform exercise are involved, and these are barriers for many that make regular physical activity a bitter pill to swallow. For years philosophers, leaders, and physicians have extolled the virtues of regular physical activity, but only in the recent decades have scientific data emerged from research by exercise physiologists, preventive medicine physicians, and other professionals to prove the benefits. Greatest benefits are incurred when very sedentary people begin and maintain a regular program of physical activity. Therefore, from a public health viewpoint, getting the most physically inactive portion of the population to become moderately active will lead to the strongest health gains. To avoid the pitfalls of sedentary lifestyle and address the first or health-related “tier” of fitness, the American College of Sports Medicine (ACSM), the American Heart Association (AHA), and the U.S. Centers for Disease Control and Prevention (CDC) recommend that every adult perform cardiorespiratory endurance exercise at moderate intensity 30 min a day 5 days a week or at vigorous intensity 20 min a day 3 days a week and accomplish 8 to 10 muscular strength training exercises, 8 to 12 repetitions of each exercise, twice a week. This first “tier” is gender specific and occupationally independent, whereas the second or performance/occupational-related “tier” of fitness is specific to one’s occupation or athletic activity and independent of gender. To address this second “tier” of fitness, one must, for most occupations and sports, physically train with greater exercise volume and specificity, usually transcending the basic first “tier” physical activity recommendations.

1.6.2.3 Components of Physical Fitness. Operational definitions of physical fitness vary with the interest and need of investigators and instructors (CDC). Dividing the construct of physical fitness into components allows for measurement.

Health-Related Physical Fitness – Health-related components of fitness are cardiorespiratory endurance, body composition, muscular strength, muscular endurance, and flexibility-mobility-stability. These health-related physical fitness components are least affected by genetics, hence more modifiable via behavior change, and are more important to both health and performance than are the skill-related components. Each component is a movement-related trait or capacity that is generally independent of the others. An underlying concept here is -- better status in each of the constituent components is associated with both lower risk for development of disease or functional disability and higher performance capacity. Again, this multifactorial construct of several components is most important for both health and performance.

- *Cardiorespiratory Endurance* – Ability to perform large muscle, dynamic, moderate-to-high intensity exercise for prolonged periods. Performance of such exercise depends on the functional state of the respiratory, cardiovascular, and skeletal muscle systems. It is more simply defined as the ability to produce energy; your level of aerobic fitness determines how long and how hard you can exercise.
- *Body Composition* – Relative percentage of body mass that is fat and fat-free tissue.
- *Muscular Strength* – The maximal force that can be generated by a specific muscle or muscle group (properly expressed in Newtons, although kg is

commonly used). It is more simply defined as the ability of your muscles to move your body and the objects around you.

- *Muscular Endurance* – The ability of a muscle group to execute repeated contractions over a period of sufficient time duration to cause muscular fatigue, or to statically maintain a specific percentage of maximum voluntary contraction for a prolonged period of time. It is more simply defined as how long your muscles can perform a task, move objects, or successfully hold items or a position.
- *Flexibility* – The maximum ability to move a joint through a range of motion. Many believe flexibility is lost with age; while this may be true, it is primarily due to the decrease in activity associated with age. Note: *Mobility* and *stability* are terms recently combined with flexibility in this final health-related component to designate a broader term that encompasses the role of stability and mobility in posture and daily functional living. Stability deals with maintaining nonmovement functional positions, including postural stability. Stability ranges from shoulder to ankle with shoulder, core, and hip stability as primary. Mobility, similar to stability, is stable, controlled, functional movement through an active range of motion in the various planes of motion.

<u>Skill-Related Physical Fitness</u> – Skill-related components of fitness are *agility, balance, coordination, power, reaction time,* and *speed*. These components are more genetically dependent than the health-related components and play a role in some AF specialties (occupation specific).

<u>Performance-Related Physical Fitness/Total Fitness</u> – Includes both health-related components plus skill-related components of physical fitness and may be termed total fitness. Note that "Total Fitness" (the complete ability to perform physical activity) = Health-Related Fitness + Skill-Related Fitness. Although the skill-related components are particularly important to athletes and some AF occupations, the five health-related components are most important for daily functional living and weight gain prevention. Interestingly, research shows that fit athletes who become *in*active are less fit than nonathletes who remain consistently active. So, to perform your daily tasks with vigor and alertness, without undue fatigue, and with ample energy to enjoy leisure time pursuits and meet unforeseen emergencies, you should focus your lifelong physical activity on the five health-related fitness components above.

1.6.2.4 Exercise Prescription/Professional Guidelines.

<u>Exercise Program Goal and Objectives</u> – The fundamental goal of a physical fitness program is to bring about a change in personal fitness behavior to enhance health and performance, which includes, at a minimum, habitual physical activity. This regular physical activity should result in long-term exercise compliance and attainment of individual fitness goals and objectives. As addressed above, these individual fitness goals and objectives are either at "tier one" – gain health benefits, prevent hypokinetic (inactivity) disorders, and maintain functional capacity, or at "tier two" – seek to attain greater health benefits and higher levels of fitness/human performance by engaging in physical activity of more vigorous intensity and greater volume (longer duration and greater frequency). To meet exercise goals, one must carry out an exercise prescription.

Exercise Prescription – Purpose/Art – The art of exercise prescription (Ex Rx) is the successful integration of exercise science with behavioral techniques that result in long-term program compliance and attainment of an individual's goals; i.e., techniques presented should be applied with flexibility and careful attention to the needs of the individual. Various purposes of Ex Rx include promoting health, enhancing physical fitness, and ensuring safety during exercise. Based on individual interests, health needs, clinical state, and performance status, these purposes of Ex Rx do not carry equal or consistent weight. Specific individual outcomes are the ultimate target for the Ex Rx.

Recommended exercise guidelines from leading professional organizations address the first tier and are listed just below. This document addresses both tiers; to meet tier one and tier two goals and objectives, one must execute a balanced exercise program that trains the human energy systems and follows primary exercise principles, addressed in the sections following these exercise guidelines.

Overarching Guidelines – ACSM, AHA, U.S. Department of Health and Human Services (HHS), CDC

2007 Physical Activity & Public Health Guidelines of the ACSM and the AHA

Guidelines for healthy adults under age 65 – Basic recommendations from ACSM and AHA:

- Do moderately intense cardio 30 min a day, 5 days a week

or

- Do vigorously intense cardio 20 min a day, 3 days a week

and

- Do 8 to 10 strength training exercises, 8 to 12 repetitions of each exercise, twice a week.

Moderate-intensity physical activity means working hard enough to raise your heart rate and break a sweat yet still being able to carry on a conversation. It should be noted that to lose weight or maintain weight loss, 60 to 90 min of physical activity may be necessary. The 30-min recommendation is for the average healthy adult to maintain health and reduce the risk for chronic disease. For further info: http://www.acsm.org//AM/Template.cfm?Section=Home_Page

2008 Physical Activity Guidelines of the HHS

Key Guidelines for Adults:

- All adults should avoid inactivity. Some physical activity is better than none, and adults who participate in any amount of physical activity gain some health benefits.
- For substantial health benefits, adults should do at least 150 min (2 hr and 30 min) a week of moderate-intensity aerobic physical activity, or 75 min (1 hr and 15 min) a week of vigorous-intensity aerobic physical activity, or an equivalent combination of moderate- and vigorous-intensity aerobic activity. Aerobic

activity should be performed in episodes of at least 10 min, and, preferably, it should be spread throughout the week.

- For additional and more extensive health benefits, adults should increase their aerobic physical activity to 300 min (5 hr) a week of moderate-intensity aerobic physical activity, or 150 min a week of vigorous-intensity aerobic physical activity, or an equivalent combination of moderate- and vigorous-intensity activity. Additional health benefits are gained by engaging in physical activity beyond this amount.
- Adults should also do muscle-strengthening activities that are moderate or high intensity and involve all major muscle groups on two or more days a week, as these activities provide additional health benefits.

For further info: http://www.health.gov/PAGuidelines/pdf/paguide.pdf

CDC

Physical activity is anything that gets your body moving. According to the *HHS 2008 Physical Activity Guidelines for Americans*, you need to do two types of physical activity each week to improve your health – aerobic and muscle strengthening.

For important health benefits adults need at least:

- 2 hr and 30 min (150 min) of moderate-intensity aerobic activity (i.e., brisk walking) every week *and*
- muscle-strengthening activities on two or more days a week that work all major muscle groups (legs, hips, back, abdomen, chest, shoulders, and arms).

or

- 1 hr and 15 min (75 min) of vigorous-intensity aerobic activity (i.e., jogging or running) every week *and*
- muscle-strengthening activities on two or more days a week that work all major muscle groups (legs, hips, back, abdomen, chest, shoulders, and arms).

or

- an equivalent mix of moderate- and vigorous-intensity aerobic activity *and*
- muscle-strengthening activities on two or more days a week that work all major muscle groups (legs, hips, back, abdomen, chest, shoulders, and arms).

For further info: http://www.cdc.gov/

1.6.2.5 Metabolic Energy Production (Energy Systems). See section 1.6.17 (Macronutrients).

1.6.2.6 Muscle for Movement – Fiber Types. Skeletal muscle contains two major fiber types, slow twitch (ST) and fast twitch (FT), classified by speed of action. Myosin ATPase, the enzyme that catalyzes adenosine triphosphate (ATP) to adenosine diphosphate (ADP) + inorganic phosphate (Pi) + energy for muscle filament action (myosin filament binding to actin filament), is in a slow form for ST and a fast form for FT. Further classification of muscle fibers is based on the characteristics of the fibers. ST or Type I fibers have high oxidative capacity but slow contractile speed, hence the label SO for slow oxidative. ST fibers also have low glycolytic capacity and low motor

unit strength but high fatigue resistance. FT or Type II fibers have low oxidative capacity but fast contractile speed, hence the label FG for fast glycolytic (for glycolysis for energy production). FT fibers also have high motor unit strength but low fatigue resistance. FT fibers are further divided into Type IIa and Type IIb or FOG (fast oxidative glycolytic) and FG. Type IIa or FOG has characteristics intermediate to ST and FG; endurance training can transition FT Type IIb towards FOG Type IIa.

1.6.2.7 Exercise Principles. Within any exercise program, certain principles apply. Understanding these principles will not only provide a solid foundation for a lifestyle of physical activity and human performance but will also help one recognize false claims about exercise and fat gain prevention. Ten primary principles of exercise follow.

1. Overload: To obtain health and fitness improvements, i.e., an overall change in the body, physical activity must place a demand on the body at a level beyond its current ability. The appropriate overload for each person can be achieved by varying the combinations of frequency, duration, and intensity of the physical activity. Regular physical activity is, in essence, a series of small challenges that gradually bring about improvement of body systems. As adaptation occurs, more load is necessary for continued improvement. This concept of individual and progressive overload applies to all, from the very sedentary unfit person to the elite athlete.
2. Progression: To avoid injury, illness, and discouragement with program progress, we must be patient with the exercise prescription and therefore ensure that increases in duration, frequency, and especially intensity of activity occur in a gradual fashion. This is especially important in the first 2 to 3 weeks of starting a new program or activity regime. Major physiological improvements take at least a few weeks, so without a certain measure of patience some people who fail to see immediate improvement will unfortunately resume an inactive lifestyle – don't fall prey to this. Stick with the Ex Rx and positive changes will occur over time.
3. Regularity: We cannot store fitness or health benefits, so we must remain active; a physical activity/exercise stimulus must occur at minimal levels of duration and frequency over time and over the life span. There is an element of truth to the adage "Use It or Lose It."
4. Balance: A balanced activity/exercise program is necessary to address the components of fitness and, in turn, prevent fat gain and obtain health benefits and performance improvements. Additionally, moderation goes hand in hand with balance. Temper zealous dedication with judgment and moderation and beware of "overtraining" – too much or too sudden can be harmful.
5. Specificity: Health benefits and body fat gain prevention are not highly specific to a certain type or mode of activity as long as the activity involves some whole body movement that meets the basic minimal exercise prescription requirements. However, specificity does apply to a certain degree in fitness in that gains or adaptations in fitness are fairly specific to the mode or type of activity/exercise applied. For example, swimming and running are activities that will improve aerobic fitness, but a swimmer will tend to perform at higher levels in swimming than in running and vice versa.

6. Variety: To keep a fresh outlook on physical activity and to prevent boredom, staleness, and the consequences of a one-dimensional program, it's a good idea to select a variety of activities. Also, we recommend a hard-easy format: a hard session followed by an easy one, long with short, fast with slow. Avoid the same routine each day but remain consistent, and try not to sacrifice the other exercise principles addressed here.
7. Recovery: Another adage that is important is "Rest is Part of Adaptation." Including easy or off days in the activity schedule, varying the intensity of activity sessions, and obtaining adequate sleep all permit physical adaptations to take place. Proper recovery also helps prevent injury and illness while helping to keep a positive view of regular physical activity.
8. Individual Response/Differences: Man was created with varying capacities to adapt to exercise. Many factors can potentially contribute to this – heredity, age, nutrition, rest and sleep habits/patterns, fitness level, attitude/motivation, environmental influences, disease, or injury. Therefore, be aware of specific attributes, limitations, and needs. Also, one must remember to compare individual gains to one's own baseline fitness level and fixed standards, not necessarily to others.
9. Reversibility/Regression/Use and Disuse: Unfortunately, the gains achieved through regular physical activity/exercise are lost with inactivity. Physical *in*activity results in flabby muscles, weak heart, poor circulation, shortness of breath, excess body fat, weakening of bones and connective tissue, and other disuse problems. As stated above, a fit athlete who becomes inactive will be less fit than a nonathlete who has remained physically active via a proper exercise prescription. Again, *in*activity is the culprit. The body does not necessarily wear out; rather, it thrives on activity. Therefore, combat disuse problems with a maintenance program of physical activity, full of enjoyable exercises and activities.
10. Potential: Everyone has a ceiling of maximal physical performance, and few achieve it or necessarily need to do so. However, through regular moderate physical activity, one can reach a reasonable percentage of potential, improve quality of life and longevity, better face life's trials and challenges, and avoid the consequences of *in*activity mentioned above.

Few programs have been validated for specific performance outcomes in the aviation and operational environment. For example, it is well accepted that higher anaerobic strength is only one component of G-performance in a high sustained G aircraft. The endurance component of a sustained duration mission must be coupled with good core strengthening and muscle tone. Likewise, balanced aerobic and anaerobic conditioning is critical for the Battlefield Airman to perform the myriad of activities in a typical mission.

1.6.3. Designing and Planning

1.6.3.1 Designing an Exercise Training Program. It is a good approach in exercise program design to work from general to specific and keep program goals at the forefront. Elite athlete training programs often start with multiyear layouts and goals with more specific annual and seasonal objectives. Similarly, the human performance training program for the military member should be designed with training periods or

cycles over time in mind. To optimally reach goals and objectives, reduce injury/illness rates, and best prescribe rest periods, program designers can lay out physical training stimuli in a progressive step-wise fashion over the following breakouts:

- Annual Cycle – Training cycle of 1 yr that consists of three or four macro training cycles.
- Macro Cycle – Training cycle of 3 to 4 mo duration that consists of three or four meso training cycles. The macro cycle should be the longest duration of continuous training prior to an active rest period.
- Active Rest – A rest period, usually 7 days to 10 days in duration, from the just completed macro cycle that must not include the same physical and mental stimuli of the recent macro cycle. However, the active rest period should include physical activity that is less structured, mentally refreshing, and different in modality, e.g., a swimmer does not swim during the rest period but plays tennis and cycles.
- Meso Cycle – Training cycle of 1 mo duration that consists of weekly micro cycles. Within a macro cycle, each meso cycle builds upon the previous meso cycle in a progressive pattern of training stimuli/exercise prescription application. Recommend scheduling a slight downturn in training stimuli at the end of each meso cycle to aid in overall physical and mental progress, e.g., weekly training volume (swim mileage, resistance training volume) increases each week for 3 weeks and then returns to baseline for week four before repeating at slightly higher levels for the next meso cycle.
- Micro Cycle – Training cycle of 1 week duration that consists of daily general workout sessions. Within a micro cycle the training stimuli can follow a hard-easy-hard format or a hard-hard-easy format. Hard and easy are defined by the combination of frequency, duration, and intensity.

1.6.3.2 General Workout Session. The salient phases of a recommended general workout session that ensure a comprehensive approach are described below in the following order: Movement Preparatory Phase, Cardiorespiratory Endurance (Aerobic) Phase, Muscle Fitness Phase, Combined Activity Phase, Skill Phase, and Movement Transition/Cessation Phase.

1.6.4. Movement Preparation

1.6.4.1 Warm-Up. Unlike static stretching (more on this in Movement Transition/Cessation Phase), activity-specific warm-up prior to exercise does enhance performance and reduce injury risk. Warm-up should always precede physical activity to increase body temperature and blood flow and to guard against muscle, tendon, and ligament strains and tears. Recommend warm-up of 10-20 min depending on the environmental conditions.

1.6.4.2 Dynamic Drills. In addition to warm-up, dynamic drills are helpful to complete the movement preparation phase by providing slight core temperature increase, enhanced blood flow/perfusion, and joint capsule lubrication. These are:

- Leg swing, fore-aft
- Leg swing, side-side
- Hi knee, hi toe
- Leg over (supine)
- Knee to chest (supine)
- Bent leg over-Scorpion (prone)
- Walking knee lift
- Carioca
- Carioca with quick step
- Backward run
- Lunge step + hip up

1.6.5. Cardiorespiratory Endurance

Again, cardiorespiratory endurance is the ability to perform large muscle, dynamic, moderate-to-high intensity exercise for prolonged periods. Cardiorespiratory endurance or cardiorespiratory fitness is the sum physiological capability of the pulmonary system, cardiovascular system, and relevant musculature at rest, during submaximal exercise, maximal exercise, and prolonged work. Many terms have essentially the same meaning as cardiorespiratory endurance: cardiorespiratory fitness; maximal oxygen consumption or uptake; aerobic fitness; functional capacity; physical work capacity; cardiovascular endurance, fitness, or capacity; and cardiopulmonary endurance, fitness, or capacity. It is important to measure cardiorespiratory endurance for exercise prescription, progress, feedback, and motivation in an exercise program; prediction of medical conditions and further diagnoses of health problems; and performance status.

1.6.5.1 Exercise Prescription for Cardiorespiratory Endurance Training. As stated above, the basic goals and objectives of an exercise program focus on health and performance. In seeking to achieve these objectives, an exercise program must place primary emphasis on cardiorespiratory endurance or aerobic fitness. In turn, the key components in an exercise prescription for cardiorespiratory endurance training are modality, frequency, duration, and intensity of exercise.

<u>Modality or Type of Activity</u> – This is a major factor in an Ex Rx. Generally, if one meets the minimum thresholds for frequency, duration, and intensity of exercise, then the overall cardiorespiratory fitness improvement is fairly independent of the mode of activity. For an individual program, select activities based on interests, abilities, time availability, equipment, facilities, and personal goals. Studies show that maximal improvements in aerobic fitness occur when the activity:

- Involves a large proportion of total muscle mass
- Maximizes use of large muscles, e.g., muscles around the thigh and hip
- Involves dynamic, rhythmic muscle contractions
- Minimizes static contractions and use of small muscles

Many modes of activity meet the above requirements. These include cross-country (Nordic) skiing, running, cycling, swimming, skating, rowing, walking, aerobic dance, indoor aerobic exercise machines (e.g., cycle ergometer, elliptical, rower, versa climber, stair), and some sports *if* they are continuous in nature (soccer, basketball, court sports). In battlefield-oriented military training programs, the primary cardiorespiratory endurance training modalities are running, swimming, and ruck marching with nonambulatory alternate cardiorespiratory endurance training activities included in the program to aid in injury prevention and add variety. In aviation-related training programs, the primary training modalities are generally less specific but can include neck strengthening exercises (fast jet) and abdominal strengthening exercises (reduction in lower back pain and better preparation for AGSM).

Frequency, Duration, Intensity – The final three steps in a proper Ex Rx are frequency or "How Often," duration or "How Long," and intensity or "How Hard." Frequency, duration, and intensity (FDI) are interrelated, and one must exceed minimum thresholds in each to achieve gains in aerobic fitness. Furthermore, this threshold will increase as aerobic fitness improves. Table 1.6.5-1 below shows the minimum, optimal, and do-not-exceed (safety) levels for cardiorespiratory endurance Ex Rx.

Table 1.6.5-1. Exercise Prescription – Frequency, Duration, Intensity

FDI	Frequency (days/wk)	Duration (min)	Intensity (beats/min)
Minimum	3	20	Minimum Heart Rate
Optimal	4-6	30-45	Target Heart Rate
Do-Not-Exceed	6	60	DNE Heart Rate

Initial military training should prescribe minimum levels for FDI and gradually move towards optimal levels as training progresses. Program design must include combinations of moderately intense and vigorously intense aerobic activity.

Intensity Determination – Moderately intense aerobic activity equates to continuous exercise that raises heart and respiratory rates, initiates sweating (varies with climate), and permits conversation; vigorously intense aerobic activity elicits higher physiological responses and permits light or broken conversation. One can objectively assess intensity of exercise via heart rate (HR) formulas.

Maximal HR Formula – Aerobic activity corresponding to HRs in the range of 60%-90% of age-specific estimated maximal HR (220 – age in years).

Karvonen Formula, the HR Range or HR Reserve Formula – Preferred method as percent HR range directly correlates with percent VO_2 max. Steps are:

1. Calculate maximal HR by subtracting age in years from 220. Max HR = 220 – age or 205 – 0.5 age and (230 –age for females).
2. Measure resting HR for 3 to 4 days shortly after waking for a 60-s period while in the same body position each day. Take an average of the measures.
3. Calculate HR range. HR range = maximal HR – resting HR.

4. Calculate minimum, optimal (target), and do-not-exceed (safety) exercise HRs:
   - Minimum exercise HR = (50% HR range) + resting HR
   - Optimal exercise HR = (75% HR range) + resting HR
   - Do-not-exceed exercise HR = (85% HR range) + resting HR

For example, a 30-yr-old AF member with a resting HR of 70 beats/min (BPM) calculates maximal HR as 220 – 30 = 190 BPM and HR range as 190 – 70 = 120. Applying the equations:

- Minimum exercise HR = 50% (120) + 70 = 60 + 70 = 130 BPM
- Optimal exercise HR = 75% (120) + 70 = 90 + 70 = 160 BPM
- Do-not-exceed exercise HR = 85% (120) + 70 = 102 + 70 = 172 BPM

Therefore, this individual should keep exercise HR above 130 BPM, but below 172 BPM, targeting 160 BPM for at least 20 min to 25 min 3 days/wk. Unfit individuals should start at the lower end of this exercise HR range. As fitness level increases, the resting HR will decrease; therefore, increase the intensity percentage from low (50%) towards optimal (75%).

Borg Scale – Measuring HRs is not always practical and sometimes problematic. An alternative is to measure exercise intensity subjectively using the Rating of Perceived Exertion (RPE) scale (Table 1.6.5-2), also known as the Borg Scale. While exercising, individuals subjectively rate how hard they are working and select a corresponding numerical rating on the RPE scale that ranges from 6 to 20. The range between 13 and 17 is needed to change aerobic fitness; however, some lifestyle health benefits can be obtained at a lower range of 12. Note that adding one order of magnitude (placing a 0) on the scale number will roughly equate to HR at the corresponding intensity, e.g., a 15 on the scale is roughly equivalent to a 150 BPM HR. Finally, ability to select individual level-of-effort will improve with consistent aerobic exercise over a prolonged period; studies show the scale has high reliability.

Table 1.6.5-2. Borg Scale

RPE Scale	Subjective Rating	Corresponding HR Equivalence (BPM)
6		60
7	Very, very light	70
8		80
9	Very light	90
10		100
11	Fairly light	110
12		120
13	Somewhat hard	130
14		140
15	Hard	150
16		160
17	Very hard	170
18		180
19	Very, very hard	190
20		200

1.6.5.2 Rate of Progression. A physiological conditioning or training effect will occur at the onset of an exercise program, especially for individuals with low initial fitness levels. Adjustments in modality, frequency, duration, and intensity are necessary to reach higher levels of health and fitness. Patience and perseverance are critical to maintain an active lifestyle and effective exercise program because many will start a physical activity program but quit within the first 2 or 3 weeks of starting and return to an *in*active lifestyle. One *must* maintain regular activity for at least 3 or 4 weeks before tangible and lasting health and performance improvements, including body fat loss, will occur. To help ensure that increases in frequency, duration, and especially intensity of exercise occur in a *gradual* fashion, the following stages of progression are helpful to avoid injury, illness, and potential discouragement (see Table 1.6.5-3).

Table 1.6.5-3. Stages of Progression Table for Healthy Individuals, General Guidance

Program Phase	Week	Frequency (sessions/wk)	Duration (min)	Intensity (% HR range)
Initial Stage	1	3	12	40-50
	2	3	14	50
	3	3	16	60
	4	3	18	60-70
	5	3	20	60-70
Improvement Stage	6-9	3-4	21	70-80
	10-13	3-4	24	70-80
	14-16	3-4	24	70-80
	17-19	4-5	28	70-80
	20-23	4-5	30	70-80
	24-27	4-5	30	70-85
Maintenance Stage	28+	3	30-45	70-85

Initial Stage – Include low level aerobic activities and light muscular endurance exercises for minimal muscle soreness or discomfort. Do not be aggressive in this stage. Set individual goals that are achievable and realistic; include a system of personal rewards. The majority of failures occur in this stage – persevere to experience benefits.

Improvement Stage – Progress more rapidly here at a higher intensity; steadily increase duration to 30 min of continuous exercise. Increase frequency as adaptation to exercise permits.

Maintenance Stage – After 6 mo of regular activity, focus on maintenance. Review goals, ensuring that long-term focus is on a lifestyle exercise behavior of consistency.

1.6.5.3 Acute Responses and Chronic Adaptations to Exercise. Extensive coverage of (1) the physiological responses to an acute bout of exercise and (2) the physiological adaptations to regular exercise training can be found in reputable exercise physiology texts and American College of Sports Medicine publications and are addressed in the USAF Exercise Principles and Methods Course.

1.6.6. Run Training

Running is likely the most common cardiorespiratory endurance exercise modality in military training. This section focuses on running, specifically distance running, but one must note that other modalities such as cycling and swimming are also quite adequate to elicit physiological training effects.

1.6.6.1 Running Performance. Three primary determinants that explain greater than 70% of the intersubject variance in distance running performance are the functional abilities:

1. Maximal Oxygen Consumption/Uptake (VO_{2max})
2. Lactate Threshold/Onset of Blood Lactate Accumulation (OBLA)
3. Running Economy

These three functional abilities have both genetic and environmental components. The genetic component is lesser and fixed, where as physical training exerts profound effects on the three determinants and, in turn, performance.

Maximal Oxygen Consumption/Uptake (VO_{2max}) is expressed as the maximal volume of oxygen taken in, transported, and used by the pulmonary, cardiovascular, and skeletal muscular systems. The true or gold standard laboratory measurement of VO_{2max} is the collection and analysis of expired air samples during exercise of progressing intensity to maximal levels. The final measure is expressed in (1) volume of oxygen consumed per minute (liters $O_2 \cdot min^{-1}$) as absolute VO_{2max} for nonambulatory exercise (e.g., cycling), or (2) more typically as volume of oxygen consumed relative to body weight per minute ($mL \cdot O_2 \cdot kg^{-1} \cdot min^{-1}$) for ambulatory exercise (e.g., running).

The interaction between cardiac output and arterial-venous oxygen (O_2) difference defines VO_{2max} or cardiorespiratory endurance. Cardiac output, the product of heart rate (HR) and stroke volume (SV), is the amount of oxygenated blood pumped by the heart per minute. Arterial-venous oxygen difference is the difference between the oxygen content of the arterial blood and the oxygen content of the venous blood, which equals the amount of oxygen extracted by the tissues – primarily the working muscle. The product of cardiac output and arterial-venous oxygen difference is the rate at which the body tissues are consuming oxygen.

$$VO_{2max} = [HR\ (b \cdot min^{-1}) \cdot SV\ (mL \cdot b^{-1})] \cdot [a\text{-}v\ O_2\ diff\ (mL\ O_2 \cdot mL^{-1})]$$

VO_{2max} or cardiorespiratory endurance is measured as above in the laboratory via a progressive maximal test to volitional exhaustion. VO_{2max} may also be predicted via field tests or submaximal exertion tests. Field tests include walk, walk-run, run, cycle, or swim tests for a set time or for timed completion of a specified distance. For optimal prediction of maximal O_2 consumption, these are maximal efforts with strong motivation and some sense of pacing. Submaximal tests predict VO_{2max} from submaximal measures of efficiency of measured variables (usually HR response). Step, treadmill, cycle ergometer, or other exercise modes are used with single- or multiple-stage protocols.

Lactate Threshold/OBLA

- Lactate Threshold (LT) – the point at which blood lactate accumulates above resting levels during exercise of increasing intensity; turn point on curve.
- Onset of Blood Lactate Accumulation (OBLA) – the point at which blood lactate accumulation begins, approximately 4 $mmol \cdot L^{-1}$.
- LT determines the fraction of VO_{2max} that can be sustained, usually expressed in terms of percent VO_{2max}. For two individuals with the same VO_{2max}, the one with the higher LT or OBLA will elicit the better performance.

Running Economy – Oxygen cost per rate of work; better economy equates to a lower VO_2 value for the same rate of work. How efficient the runner is at converting available energy into running velocity. Dependent on percent slow twitch fibers, mechanical efficiency, musculotendonous stiffness, and ventilatory cost.

1.6.6.2 Chronic Adaptations to Exercise Run Training/Training to Improve. Current run training methods have largely developed from a trial-and-error approach of runners and coaches, while contributions from scientists have been relatively small due to a variety of reasons, including reluctance of coaches to acknowledge potential merit of research for improving training methods and scientific research has been limited by methodological problems. Therefore, available training methods often include elements of sound principles mixed with questionable or nonefficacious methods. Program designers must view traditional-historical methods with caution and always ask, "Why should I include this in my program?" Finally, scientists can still provide valuable training recommendations by integrating information from the limited quality training studies with related scientific knowledge. Run training elicits changes in morphological/physiological components across the three determinants of performance.

VO_{2max} – Two General Means

- Morphological/physiological factors – Central
  - Increase left ventricular chamber size and wall thickness – increased SV
  - Increase plasma volume – increased blood volume (BV) and SV
  - Increase erythrocyte mass – increased BV, SV, arterial O_2 content
- Training to improve central factors: intensity, at or near VO_{2max} training. Time spent at VO_{2max} – control the recovery intervals

- Morphological/physiological factors – Peripheral
  - Increased skeletal muscle mitochondrial density and oxidative enzyme content (and proximity) – increased widening of arterial-venous O_2 difference
  - Increased skeletal muscle capillarity – increased O_2 diffusion and uptake
  - Increased myoglobin concentration – increased O_2 diffusion from sarcolemma to mitochondria
- Training to improve peripheral factors – volume, submaximal training; base and maintenance work
- Higher the VO_{2max} the less dependence on anaerobic capacity (which is limited); lower the RPE at same work rate

- Goal is not necessarily to tolerate lactic acid (H+) buildup but to reduce lactic acid buildup at race pace – do so by increasing aerobic contribution, which is one means of increasing LT pace

Lactate Threshold/OBLA

- Morphological/physiological factors
  - Changes in anaerobic enzymes (decreased phosphofructokinase (PFK), changes in lactate dehydrogenase (LDH) and monocarboxylate transporter (MCT) isoform) – decreased lactate production
  - Increased skeletal muscle mitochondrial density and oxidative enzyme content – increased pyruvate to Krebs cycle versus lactate production
  - Increased beta oxidation enzymes – increased lipid oxidation, decreased demand for carbohydrate (CHO) metabolism and lactate production at given work rate
  - Increased muscle strength – reduced recruitment of Type II fibers and reduced blood flow occlusion
- Training to improve
  - Threshold runs, interval runs (same as with VO_{2max})
  - Also repetition runs
  - Some muscle fitness training, especially "aerobic rotations"

Running Economy

- Morphological/physiological factors
  - Change in FT towards ST (FOG) muscle fiber- reduced energy cost per given force production
  - Increased mechanical efficiency – reduced whole body energy demand
  - Increased musculotendonous stiffness – increased storage and return of elastic energy and muscle stabilization
  - Decreased minute ventilation for a specific run velocity – reduced respiratory energy demand
- Typically improves with increased training time (chronic) and concomitant improvement in running skill
- Cumulative distance over years of training, not the training volume per se
- Training to improve
  - Long runs
  - Repetition runs
  - Muscle fitness work – resistance training, plyometrics, stability-mobility (core)/elasticity, stiffness

Brief Summary of Training to Elicit Adaptations

- Quantity to quality spectrum includes: long, steady state, threshold, hills, fartlek, interval, and repetition runs/other training
- Program designer must determine and balance the training load – a product of intensity, duration, and frequency. Leaders may prescribe training load based on training volume (duration x frequency), i.e., miles per week. However, one

must not forget intensity, considered the most important variable in training. Intensity may be prescribed as percentage of maximum velocity or race pace or percentages of physiological variables – percent VO_{2max} or percent HR max.

- A balance of quantity and quality must be included to elicit improvements in the three primary determinants above. Generally, quantity runs affect VO_{2max} peripheral factors and running economy while quality runs affect all three determinants.

1.6.6.3 Run Ability Groups. When training in groups, e.g., students in a course, it is efficacious to employ ability groups to provide optimal application of the physical training stimulus. Group individuals according to their estimated VO_{2max} determined from a baseline run test, i.e., the 1.5-mi run (sample grouping below in Table 1.6.6-1). Conduct training runs (steady state, interval, fartlek) by ability group.

Table 1.6.6-1. Sample Run Ability Groups

Ability Group	1.5-Mi Test (min:s)	Estimated VO_{2max} (mL O_2/kg/min)
A+5	≤9:12	≥56
A++++	9:13-9:45	53-55
A+++	9:46-10:10	51-52
A++	10:11-10:37	49-50
A+	10:38-11:06	47-48
A	11:07-11:38	45-46
B	11:39-12:14	43-44
C	12:15-12:53	41-42
D	12:54-13:36	39-40
F	≥13:37	≤38

1.6.6.4 Run Training Methods. Several modes of run training from the quantity to quality spectrum include long,steady state, fartlek, hill, threshold, interval, and repetition runs along with other training.

<u>Assessment Runs</u> – Runs that include baseline tests, course evaluations, or races that are typically run on flat measured courses such as 400-m tracks or roads. In putting forth a maximal best effort, runners should employ a race plan to achieve the best time for distance and apply learned pacing technique with the use of watches.

<u>Long and Steady State</u> – Runs that are longer in duration (up to an hour or more) and lower in intensity than other running modes employed. Duration is of import here; run these at a nonstraining intensity (Table 1.6.6-2). Long and steady state runs primarily affect the portion of aerobic metabolism that occurs in the muscle cell, improving the working muscles' ability to take up and use oxygen for energy production. In addition to building cardiorespiratory endurance, these runs also enhance the musculoskeletal system; therefore, these runs build the base for more intense workouts. Intensity for these runs is 65%-79% of HR max, 59%-74% of VO_{2max} or Karvonen HR reserve (as stated above, the percent Karvonen HR range is identical to the HR equivalent of the same percentage of VO_{2max}), or an RPE of 12-13. These runs form a strong foundation

for the weekly mileage base. The periodic (every 7 to 10 days) long run should amount to no more than 25% of total weekly training mileage. These may be run on grass and dirt surfaces across fields, over hills, through woods, or on roadways. Running on asphalt should be reduced as much as possible, and running on concrete should be avoided.

Table 1.6.6-2. Run Training Pace (Intensity) Guide

Ability Group	1.5-Mi Test (min:s)	Long/ Easy Pace (min/mi)	Fartlek Base Pace (min/mi)	Threshold Pace (min/mi)	Interval Pace (min/400 m)	Repetition Pace (min/400 m)
A+5	≤9:12	≤8:36	≤7:20	≤6:54	≤1:35	≤1:28
A++++	9:13-9:45	9:04	7:45	7:17	1:40	1:33
A+++	9:46-10:10	9:25	8:04	7:34	1:44	1:37
A++	10:11-10:37	9:47	8:24	7:52	1:48	1:41
A+	10:38-11:06	10:10	8:46	8:12	1:53	1:46
A	11:07-11:38	10:36	9:09	8:34	1:58	1:51
B	11:39-12:14	11:05	9:36	8:58	2:03	1:57
C	12:15-12:53	11:37	10:04	9:24	2:10	2:03
D	12:54–13:36	12:11	10:35	9:53	2:16	2:10
F	≥13:37	≥12:12	≥10:36	≥9:54	≥2:17	≥2:11

Fartlek – The Swedish word for “speed play”; a type of running that improves mental and physical abilities to adapt to varied intensity, duration, and terrain. In the beginning (first 5-8 min) of a fartlek run, leaders should establish a base pace (Table 1.6.6-2), which is slightly faster than long-steady state pace but slower than threshold. Thereafter, instructors should inject surges of varied intensity and duration/distance (50-1200 m) into the base pace. Fartlek run leaders should ensure runners are not “in formation” on these runs; rather runners should run in a loose cluster or “beehive” grouping, maintaining visual awareness and not watching legs and feet of other runners. Runners strive to stay within 10 m of the leader but can fall back as much as 200-400 m if visual contact is maintained. Leaders can employ teardrop turns to accommodate slower runners.

Hill – Included in steady state and fartlek runs to improve running fitness and form.

Threshold – Run as a steady state run but at slightly higher intensity that pushes the limit of aerobic metabolism. The intensity of threshold runs, 88%-92% of HR max, 83%-88% of VO_{2max} or Karvonen HR reserve, or an RPE of 14-16, approaches the anaerobic threshold or level where anaerobic metabolism nearly supplies a portion of the necessary energy. The “comfortably hard” intensity is roughly between 10 km and half marathon race pace (Table 1.6.6-2). Threshold runs should be limited to approximately 10% of total weekly training mileage.

Interval – Repeated bouts of shorter run distances, typically 100 to 1600 m in work distance, interspersed with rest periods designed to improve (1) cardiovascular system’s ability to deliver oxygen to your working musculature, (2) pacing ability, and (3) running form. Concerning the cardiovascular system, interval runs primarily affect the central factors, stimulating an increase in left ventricular chamber size and wall thickness and expansion of blood volume, leading to an increase in stroke volume and concomitant reduction in heart rate for the same work rate. The intensity of interval runs is 98%-100% of HR max, 94%-100% of VO_{2max} or Karvonen HR reserve, or an

RPE of ≥ 17 (see Table 1.6.6-2 for interval pace guidance for 400-m work distance). This intensity is at or near VO_{2max}, and the total time spent at VO_{2max} is essential for optimal results; therefore, one must control the recovery intervals. Leaders should monitor these closely to ensure runners start the next repetition on time (see *sample* guidance in Tables 1.6.6-3 and 1.6.6-4). The goal for the runner is controlled pacing across the work repetitions: maintain at or slightly faster than ability group goal pace across the entire workout. Starting out the initial repetitions at a faster than goal pace and slowing across the workout is worse than remaining consistent across the workout a few seconds slower than pace. Traditional intervals cross the anaerobic threshold (AT) and have both aerobic and anaerobic components for energy supply.

<u>Repetition</u> – Repeated bouts of shorter run distances, typically 100 to 400 m in work distance, interspersed with rest periods designed to primarily improve running economy, running mechanics, and speed for goal race pace. Secondarily, these runs will also help improve anaerobic or lactate threshold. See Table 1.6.6-2 for repetition pace guidance for 400-m work distance. Repetition pace is employed for some of the shorter work distances in the sample guides found below in Tables 1.6.6-3 and 1.6.6-4.

Table 1.6.6-3. Sample 8-Week Interval Run Guide, Ability Groups A-F

Wk	Sets x Reps x Work Distance (m)	Work:Rest Ratio	Set Rest (min)	Ability Group				
				A	B	C	D	F
1	2x3x300	1:0.5	2:00	1:26	1:29	1:35	1:39	1:40
2	2x4x400	1:0.5	3:00	1:58	2:03	2:10	2:16	2:17
3	1x3x1200	1:0.5	N/A	5:53	6:10	6:29	6:49	6:50
4	1x3x600	1:1	3:00	2:46	2:55	3:04	3:15	3:16
	2x4x200	1:1	3:00	0:55	0:58	1:01	1:04	1:05
Retest 1.5-mi run, then adjust ability group								
5	1x3x800	1:1	3:00	3:56	4:07	4:19	4:33	4:34
6	1x3x600	1:1	3:00	2:46	2:55	3:04	3:15	3:16
	1x4x300	1:1	3:00	1:22	1:27	1:31	1:36	1:37
7	4x5x200	45/35/25/15 cutdown[a]	2:00	0:55	0:58	1:01	1:05	1:06
8	2x4x400	1:0.5	N/A	1:58	2:03	2:10	2:16	2:17

[a]Cutdown rest: 200-m work intervals with progressively shorter rep rest; 45/35/25/15-s rep rest for four sets, respectively, i.e., 45 s between reps in first set, 35 s between reps in second set, etc. Two minutes rest between sets.

Table 1.6.6-4. Sample 8-Week Interval Run Guide, Ability Groups A+5-A+

Wk	Sets x Reps x Work Distance (m)	Work:Rest Ratio	Set Rest (min)	Ability Group A+5	A+4	A+3	A+2	A+
1	2x3x300	1:0.5	2:00	1:09	1:13	1:16	1:18	1:22
2	2x4x400	1:0.5	3:00	1:35	1:40	1:44	1:48	1:53
3	1x3x1200	1:0.5	N/A	4:45	5:00	5:12	5:25	5:38
4	1x3x600	1:1	3:00	2:12	2:19	2:25	2:31	2:39
	2x4x200	1:1	3:00	0:43	0:46	0:48	0:50	0:52
Retest 1.5-mi run, then adjust ability group								
5	1x3x800	1:1	3:00	3:10	3:20	3:28	3:36	3:46
6	1x3x600	1:1	3:00	2:12	2:19	2:25	2:31	2:39
	1x4x300	1:1	3:00	1:04	1:09	1:12	1:15	1:18
7	4x5x200	45/35/25/15 cutdown[a]	2:00	0:43	0:46	0:48	0:50	0:52
8	2x4x400	1:0.5	N/A	1:35	1:40	1:44	1:48	1:53

[a]Cutdown rest: 200-m work intervals with progressively shorter rep rest; 45/35/25/15-s rep rest for four sets, respectively, i.e., 45 s between reps in first set, 35 s between reps in second set, etc. Two minutes rest between sets.

1.6.6.5 Run Training Plan. Each micro cycle in the run plan may contain all types or a mixture of the run types above. Alternate cardiorespiratory endurance training, indoor aerobic exercise machines (see above), should be included in the overall plan to attenuate injury risk and add variety and may be prescribed by physicians or physical therapists for partially limiting injuries. The run plan should progressively build in volume across meso cycles (≈ months) with minor volume reductions between meso cycles that, in turn, build to a complete macro cycle. A no-running active rest period should follow each macro cycle.

1.6.6.6 Run Shoes and Running Form. Quality running (versus court, cross training, or other athletic shoes) shoes are necessary for training. Shoes are classified into three basic types:

- “Cushioned” – for neutral, high arched feet with no overpronation (excess inward motion of the ankle and foot upon foot strike)
- “Stability” – for moderate to high arches with slight overpronation
- “Motion Control” – for low arches with overpronation

Running Form – One should conduct a mental checklist from head to foot to avoid biomechanical deficits in running form:

- Run with eyes forward, looking ahead, not at the feet of the person running in front of you.
- Hold head straight and steady, don't rock.
- Keep ipper body perpendicular to running direction with shoulders relaxed.
- Arms pivot at the shoulder, not the elbow joint, holding approximately an 80-deg to 90-deg angle at the elbow.
- Increase speed by increasing stride rate/turnover, not by abnormally lengthening stride.

1.6.7. Muscle Fitness

A key to a fit force is reduction of injury and improved recovery following activities. Muscle fitness is in the center of the target ring for any task that relies upon individual strength, flexibility, and movement.

1.6.7.1 Physical Endurance. Physical endurance is composed of two separate but related concepts – cardiorespiratory endurance (covered above) and muscular endurance; the former refers to the whole body whereas the latter refers to the capacity of individual or groups of musculature.

1.6.7.2 Muscle Fitness Principles. Muscular fitness is a linked term that combines muscular strength and muscular endurance and infers the interdependence between these two physical fitness (PF) components. Muscular strength is the maximum force generated by a specific muscle or muscle group, and muscular endurance is the ability of a muscle group to execute repeated contractions over a period of sufficient time duration to cause muscular fatigue. A balanced physical activity program should address the five health-related components of physical fitness, with primary emphasis on aerobic fitness, but muscular fitness is also important as inclusion of muscular strength and muscular endurance exercise provides several benefits:

- Develops muscular strength and endurance to enhance the ability to live a physically independent lifestyle, i.e., improves daily functional living.
- Increases and maintains fat-free (lean) mass, helping to maintain resting metabolic rate, which is beneficial for preventing fat gain.
- Increases the strength and integrity of connective tissue.
- Increases bone mineral density, preventing age-related bone deterioration.
- Combats chronic low back problems.
- Improves the ability of the muscles to recover from physical activity.
- Provides injury protection during deployment, daily work, and sports and recreational activities.
- Alleviates some common musculoskeletal complaints that result in lost duty time and medical treatment costs.
- May provide modest gains in cardiorespiratory fitness.
- May improve mood and self-image.

Muscular fitness exercise is essential to gain the above benefits and to develop muscular fitness to optimal human performance levels.

Overload, Specificity, and Progression – The three main principles of exercise training must be included in a muscle fitness training program. First, training must provide an overload, or a stimulus, for the muscle to adapt – the means for development of muscular strength and muscular endurance. Through adaptation muscles become stronger and better able to sustain muscular activity. Physiological adaptations to properly executed muscular fitness training include both neuromuscular adaptations and muscle cell adaptations, with the former accounting for nearly all of the overall performance gains in the first weeks of a muscle fitness training program and the latter, muscle cell hypertrophy, accounting for the majority of gains later in a program (more detail on physiological responses and adaptations to muscle fitness training can be found in reputable exercise physiology texts, ACSM publications). Secondly, training should be individualized, i.e., the principle of specificity – designed to meet individual needs. Finally, training should be progressive by including periodic increases in workload as muscular fitness improves.

Mode and Pattern – The above process of overloading the muscular system is referred to as resistance training, which includes, but is not limited to, calisthenics, weight training, plyometrics, and field exercises. This training should focus on major muscle groups in the core and lower and upper regions of the body and should address the primary movement patterns (in priority order) of run, bend, twist, squat, pull, and push.

Volume and Intensity – For general fitness and health, ACSM, AHA, and CDC recommend accomplishing 8 to 10 resistance training exercises involving all major muscle groups at least twice per week. They recommend one set of 8 to 12 repetitions of each exercise performed at moderate or high intensity to muscular fatigue. However, for higher levels of fitness with a human performance focus, one should perform multiple-set resistance training regimens. Generally, for muscular strength development two to three sets of 10 to 12 repetitions of an exercise should be conducted at a 1:1 to 1:3 work:rest ratio. Resistance load should be set so the last few repetitions of an exercise are challenging but still feasible with controlled form. For muscular endurance development, two to three sets of 15 to 20 repetitions of an exercise should be conducted at a 1:1 work:rest ratio. Finally, for muscular power development, three or more sets of fewer repetitions at longer work:rest ratios are needed. For muscular strength and endurance workouts, a maximum of 1 min to transfer between exercise stations should be allowed. Other set-repetition-work:rest combinations may be used, e.g., 1-min cycle (below in calisthenics section).

Procedures and Safety – The following resistance training procedures work in conjunction with the above recommendations:

Frequency – One can conduct resistance training nearly every day of the week (recommend no more than 6 days/wk) as long as sufficient variety and balance are designed into the program. Exercises specific to location or pattern typically are spaced across the week, i.e., ≈ every 48 hr. Different apparatus, free weights, machines, medicine balls, etc. can be used here.

Order of Execution – Try to not work the same muscle group with consecutive exercises. Rather, work the major areas of the body over the priority movement patterns at one time, i.e., core, lower, then upper with occasional mixing of exercises within major areas to maintain variety and prevent staleness in the workout routine. Also, start with exercises of greatest priority and follow with exercises of lesser importance.

Control – Training activities should be rhythmic, performed at a controlled (not necessarily slow) speed, and not interfere with normal breathing.

Range of Motion (ROM) – Conduct exercises over the joint's full ROM in a controlled manner; however, limit the ROM on open and closed chain exercises involving the knee (e.g., squats, avoid dropping past 90 degrees of flexion; leg extensions, limit to ≈ 20 deg to ≈ 60 deg of motion to protect the knee joint).

Rest Time – Keep rest time between exercises (and between sets if multiple sets are used) controlled as above. Avoiding long, time-wasting breaks results in better fitness and a more efficient workout and increases the likelihood for retaining resistance training as a lifestyle behavior.

Safety – Perform a proper warm-up, work antagonistic (opposite) muscle groups, and use a spotter if using free weights.

1.6.8. Muscle Fitness Testing

Muscular fitness testing varies in assessment tools and standardization. Prior to any testing, leaders must consider member familiarity with equipment and procedures, safety, breathing, and rest between assessments.

Muscular Strength Testing – Static or isometric muscular strength can be measured by cable tensiometers and handgrip dynamometers. Measures are specific to both the muscle group and joint angle involved in testing; therefore, their utility in describing overall muscular strength is limited. Dynamic or isotonic strength can be measured by various 1-repetition maximum (1-RM) (heaviest weight that can be lifted only once) tests. Also, isokinetic testing involves use of expensive machines that assess muscle tension generated throughout a range of joint motion at a constant angular velocity, a measurement of peak rotational force or torque.

Muscular Endurance Testing – Test by lifting a submaximal level of resistance and measuring the number of repetitions or duration of static contraction to fatigue. Measurements are conducted via machine or calisthenic field tests (push-ups, pull-ups, sit-ups).

1.6.9. Stability and Mobility

Stability and mobility are terms recently combined with flexibility in the final health-related physical fitness component to designate a broader term that encompasses the role of stability and mobility in posture, occupational functional movement, and daily functional living. Stability deals with maintaining nonmovement functional positions, including postural stability. Stability ranges from shoulder to ankle with shoulder, core, and hip stability as primary. Mobility, similar to stability, is stable, controlled, functional movement through an active range of motion in the various planes of motion. No published tests or standards are yet available for assessing mobility or stability. However, exercises that are known to enhance stability and mobility, especially in the core region, for functional fitness should be added to the muscle fitness training regimen. The core region encompasses the musculature that anchors and acts on the pelvis, providing the stable framework for motion. These muscles include the abdominals, obliques, quadratus lumborum, hip abductors and adductors, anterior hip musculature (iliopsoas group), posterior hip musculature (gluteals and tensor fasciae latae), hip rotators, and lower back muscles (erector spinae-lumbar and semispinalis).

1.6.10. Resistance Training Modes

1.6.10.1 Calisthenics. Calisthenics are body resistance exercises to improve muscular fitness, e.g., sit-ups, push-ups, and pull-ups. A calisthenics-based approach to exercise and, more specifically, exercise testing has advantages and disadvantages:

<u>Advantages</u>

- Minimal space required
- Minimal cost for mats and incidentals
- May be used in the field (outdoor)
- Historical – traditional basis: historically, military services have incorporated calisthenic-type measures as metrics (does not necessarily mean the best or optimal means for testing)
- Sister Service normative scores exist; however, not anchored in criterion standards

<u>Disadvantages</u>

- Relatively high degree of interindividual test variability (confirmed by AF feasibility testing)
- Relatively high degree of subjectivity in test administration (confirmed by AF feasibility testing)
- Not optimal scientifically; Sister Service science experts confirm significant negatives
- Traditional pattern of sit-up, push-up, and pull-up does not assess (or very limited) lower body
- Does not assess muscular strength component of PF, i.e., measures muscular endurance

- Difficult, at best, to set either health- or performance-related criterion standards for calisthenic tests

Calisthenic Methods. One of several means of physical training with calisthenic exercises is a basic set procedure that provides a fairly objective means for controlling an individual exercise prescription. The goal of this procedure is to accomplish 33% of a one-test (one-set) maximum in a three-set pattern on a controlled 1-min cycle. First, determine the current maximum number of repetitions of the exercise in a 1-min period i.e., use the most current evaluation result. Second, take 33% of that total number for the amount of repetitions to perform for each of three sets. Rest between sets is on the minute cycle, i.e., perform the first set of repetitions, rest for the remainder of 1 min, start the next set at the 60-s cumulative time mark, and start the third set at the cumulative 120-s mark. Perform these three sets of exercise once per day starting at 2 to 3 days per week, building to a maximum of 6 days per week. For example, an individual with a sit-up test maximum of 44 repetitions will perform three sets of 15 repetitions per set on the minute cycle: 15 repetitions – rest remainder of the first minute, 15 repetitions – rest remainder of second minute, 15 repetitions. Over time add repetitions to each set as the last few repetitions of the third set become easier.

Calisthenic Exercises (Limited Listing)

- *Core (Bend and Twist)* – crunch, cross-knee crunch (feet on wall), windshield wiper, hanging knee to elbow, sit-up, flutter kick, V-raise, plank series (bridges) with leg raises

- *Lower and Whole Body (Run and Squat)* – squat, lateral squat, single leg squat, lunge, walking lunge, Iron Mike, squat thrust, mountain climber, multi-count body builder, Burpee

- *Upper (Pull, Push)* – pull-up; pull-up in L-position; pull-up with partner; arm rotations; push-up series; push-up, raised (box, wall)

Weight Training – Major series of resistance exercises to improve muscular fitness that employ an external object, e.g., machine-based weights (weight stacks, cables, etc.), free weights (bars, plates, etc.), medicine balls, sand bags, weighted vests, and many more.

- *Machine and Free Weights* – Some commonly recommended resistance training exercises that are in accordance with ACSM's major muscle group recommendations are:

  - *Core* – abdominal "crunch," incline ab, barbell balance with toe touch, trunk rotator, back extension, Captain's chair

  - *Lower* – leg press, leg (knee) extension, leg (knee curl) flexion, hip flexion and extension, hip abduction and adduction, calf (heel) raise

  - *Whole* – squat, dead lift, thrusters, clean, clean & jerk, snatch

- *Upper* – (lat) pull down, seated or erect row; shoulder or push (overhead) press; bi-directional bent-arm flys (shoulder horizontal flexion and extension); chest (bench) press; arm (bicep) curl; tricep extensions or dips; running dumb bell; lateral raise

- *Weight Equipment* – For the beginner, machines are often more optimal than free weights, as machines require less skill, one can start at lower resistance and increase in smaller increments, and it's easier to control ROM. However, for intermediate and advanced weight training, free weights and other apparatus should be used

- *Medicine Balls* – Another means of weight training with high utility. A partial list of medicine ball (MB) exercises:

  - *Core* – basic rotation close, basic rotation distance with cross-over, reaching wall tap, prone leg hold with arm pass, sit-up and throw, throw from knees to pop-up, two-arm trunk push

  - *Lower* - squat MB thruster with jump/toss/turns, one-legged squat with MB rotation, mule kick

  - *Whole* - three distance rapid wall throw, log throw, wood chopper, wall ball squat thrust, overhead toss, front and rear with partner/with run chase

  - *Upper* – two-arm over, ball slam, two-arm putt, one-arm under, one-arm putt, one-arm over

- *Stability/Physio Balls, Bosu Balls, and other Unstable Platforms* – Numerous exercises can be performed with these devices to enhance neuromuscular recruitment patterns and elevate the degree of difficulty.

- *Other Weighted Objects* – Other objects for weight training include sand bags, weighted vests, bars, bands, etc.

<u>Plyometrics</u> – Activities that train a muscle to reach maximal force in the shortest possible time. Training exercise drills employed as a supplement to resistance training to develop quick, explosive, and powerful muscles. Plyometric movements are generally classified into four exercise modalities:

- Jump – two-leg take-off and landing
- Hop – single-leg take-off, landing on the same foot
- Bound – single-leg take-off, landing on the opposite foot
- Skip – single-leg take-of,f landing with two feet contact

Plyometric exercises include box, depth, squat, double, lateral jumps, and bounding.

Field Activities – These include carries and drags (buddy, rescue), weighted pulls (sleds, tires), rope pulls and climbs, crawls (low, high, bear), partner relays, grass and guerilla drills.

1.6.10.2 Functional Fitness. As in the above paragraph on stability and mobility, functional fitness training requires further development than basic fitness activities. It is physical training that addresses whole body fitness via multi-joint movement, multi-task activities that have increased functionality and relevance to AF operational/occupational actions.

1.6.11. Combination Training

1.6.11.1 Combined Activity Phase. Physical training that combines aerobic and muscular fitness actions can be quite effective for overall fitness development that, depending upon design, can contain varied degrees of functional fitness training with high occupational task relation.

1.6.11.2 Rotations. Multi-station rotations are designed courses that include cardiorespiratory, muscle fitness, and skill components. Designs vary, but in a typical rotation, members run between stations where they must accomplish muscle fitness exercises or skill requirements prior to advancing to the next station. Rotations can be designed to require a set number of requirements with time as the dependent variable or a number of requirements accomplished in a fixed time. Rotations should be designed and applied in a progressive manner, i.e., beginner, intermediate, and advanced levels with increased degree of difficulty (physical, mental, skill), task complexity, or occupational specificity.

1.6.12. Skill

Occupational- or athletic-specific skill training should be accomplished at this point of an overall general exercise session.

1.6.13. Movement Transition/Cessation – Flexibility

1.6.13.1 Cool-Down. Although frequently ignored, a brief cool-down period after an exercise session is important. Cool-down, a gradual reduction in activity, permits reduction in the elevated cardiovascular (prevents blood pooling) and metabolic systems and may hasten recovery and avoid injury.

1.6.13.2 Flexibility/Static Stretching. Flexibility is the maximum ability to move a joint freely, without pain, through a range of motion. Flexibility tends to decrease with age, primarily due to the decrease in activity associated with age. Although no single test can be generalized to evaluate total body flexibility, it is important to health and functional living and should be part of a well-balanced exercise routine.

Timing and Guidelines – Despite the popular perception that stretching prior to exercise enhances performance and prevents injury, little scientific evidence exists to support such long-held beliefs. Recent research actually shows that static stretching prior to exercise causes a temporary weakening of muscle and does not decrease the risk of

injury. Therefore, static stretching prior to exercise or an athletic event is contraindicated. Rather, engage in a gradual, activity-specific warm-up that includes the movement patterns of planned activity, e.g., if running for the workout then warm-up with brisk walking, jogging, and dynamic movements or drills such as leg swings and knee raises (above). To help maintain flexibility one should stretch after a workout when muscles, tendons, ligaments, and connective tissue are warmer (above normal body temperature). Static stretch according to the following ACSM guidelines:

- Type – static stretch, with a major emphasis on the major muscle groups to include the low back, hips, iliotibial band, quadriceps and hamstrings, calf, and shin. Do not ballistic (bounce) stretch.
- Frequency - 2 to 3 days/wk
- Duration - 10 to 30 s for each stretch
- Intensity - to a position of mild discomfort, not to point of pain
- Repetitions - two to three for each stretch

Again, first increase body temperature; don't "cold" stretch. Finally, avoid comparing one's level of flexibility to others, as it varies widely across individuals due to several factors that include gender, age, activity level, temperature, and extensibility of the muscles and tendons surrounding the joints.

1.6.14. Body Composition

1.6.14.1 Body Composition Hierarchy. Body composition deals with the relative portion of the body that is composed of fat and fat-free tissue. Body weight and body fat are related to health status, but misconceptions exist regarding body measurements and application of results. In the assessment of fat gain and associated disease risk and performance degradation, the focus must go beyond body weight measures to relative body fat and body fat distribution.

1.6.14.2 Weight and Height. Measurements of weight and weight relative to height – scale readings, height-weight tables, body mass index (BMI) – do not differentiate between fat and fat-free tissue and do not account for fat distribution pattern. Unfortunately, the societal norm for "measuring" body composition is the scale. Routine use of the home, gym, or doctor's scale enforces the misconception that body weight is more important than body fatness. BMI, an index of weight and height, is a health screen with recognized, evidence-based guidelines. However, it also cannot fully describe body composition and related health status, as it is not a direct measure of body fat, does not pick up individual changes in body fatness, and is difficult to project changes with exercise and diet via BMI alone. Therefore, scale and BMI readings can mislead one into thinking a change in body weight is a gain or loss of fat alone. Weight changes occur in fat-free components (bone, muscle, organs) as well as in fat. Many are concerned about losing weight to be thin, without realizing that thin does not necessarily equal lean. A lean person with low body fat may weigh more, due to greater muscle mass, than a thin person. Also, *in*active thin individuals may not be overweight but often are overfat, whereas lean individuals with fit muscle tissue are typically physically active. Therefore, activity, specifically aerobic and resistance exercise, is very important for preventing loss of fat-free mass and gain in fat mass.

1.6.14.3 Relative Body Fat and Body Fat Distribution. The amount of total body tissue that is fat and where fat is deposited or carried on the body are necessary to complete a body composition assessment. This is done via “non-scale” measurements.

1.6.14.4 Percent Body Fat. Total body fat relative to body mass is known as percent body fat. Average and at-risk levels are 15% and 25% for males, 23% and 32% for females, respectively.

1.6.14.5 Abdominal Circumference. Increased health risks associated with overfat are not only related to total body fat but also and more closely to fat distribution. Upper body or trunk fat, specifically abdominal fat, presents the greatest health risk; it is highly linked to cardiovascular diseases and metabolic disorders such as type II diabetes. Reducing abdominal girth or circumference is more important than normalizing body weight, since exercise-induced increases in muscle mass can mask reductions in girth, i.e., with proper exercise body weight may stay the same or even increase, but “belt size” will reduce. Therefore, as abdominal fat is an independent risk factor for disease, the evaluation of abdominal circumference (AC) is used. A high risk of current and future disease exists for males with an AC > 39 in. regardless of age or height. The health risk is moderate for males with an AC OF 35 to 39 in. and low for an AC < 35 in.

1.6.14.6 Aerobic Fitness and Visceral Adipose Tissue. With a very strong scientific connection between aerobic fitness and abdominal adiposity, unhealthy visceral fat exists. Recent and compelling research data show:

- Moderate to high levels of aerobic fitness provide health risk protection independent of body weight or total adiposity.
- Aerobic fitness provides protection, not by reducing body mass per se, but by reducing fat from the region in which it is most dangerous – reduces visceral fat.
- Aerobic fitness mitigates elevated health risk associated with increases in abdominal fat.

1.6.14.7 Spot Reducing. Finally, remember spot reducing is a fallacy. “Ab” machines may aid in strengthening abdominal muscles, but these exercises alone will not reduce abdominal fat or girth. Physical activity and caloric restriction are the best means for reducing total and regional body fat.

References

2007 Physical Activity & Public Health Guidelines of the American College of Sports Medicine (ACSM) and the American Heart Association (AHA).

Concepts (also see Glossary)

Health

Vocabulary (also see Glossary)

Exercise & Exercise physiology
Exercise training
Muscle contraction
Physical activity & Physical fitness

1.6.15. Nutrition

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Mission One: Consider the influence of preflight meals on the aircrew that is alerted to a med-evac mission at the 8th hour of a 12-hr alert period. The crew scrambled from a forward-operating base on a night combat search and rescue mission. As part of the mission, they were to transport two casualties to a forward medical station. Now 14 hr into their day, the crew could have chosen to stay in place as they were off alert status or return to their forward-operating base. The Joint Search and Rescue Center directed the crew to RTB. Following a minimal preflight briefing, the pilot performed a modified marginal power climb profile, the aircraft entered a brown-out condition, and the pilot failed to maintain forward motion, allowing the tail to strike the ground and causing the aircraft to roll inverted.

Mission Two: What influences does daily well-being have on nutritional intake? A double turn sortie was briefed at 0615 with a planned hot-pit refueling between sorties. Take-off was at 0730 with hot-pit at 0930-0950, and second take-off was scheduled for 1015. Approximately 90 min into the second sortie (6.5 hr into the pilot's day without adequate breakfast), the mission pilot began feeling sick to his stomach (nausea) with headache and dry mouth. Symptoms of nausea persisted, so he terminated the mission and RTB. Only upon examination did the pilot admit to mild gastritis exasperated by dehydration, poor nutrition, and daily aspirin therapy.

Mission Three: How does circadian rhythm influence nutrition? Mission crew is scheduled as a replacement crew over a 4-day period. Initial take-off is 0800L for an 8.2-hr sortie, with subsequent mission launches at 1230L, 1745L, and 0230L spanning a 5-day period. Each mission is scheduled to be 6.4 to 10.2 hr in length, and there is ample food available in the galley of the aircraft. Problem is shifting the body's sleep-rest schedule and eating schedule over a short period of time leaves several of the mission crew forgoing meals in place of rest.

The human body's need for nourishment is as fundamental as its requirement for oxygen. To sustain life, the body must balance whole-body energy metabolism, that is, the ingestion, degradation, and absorption of nutritional food sources for the development, growth, and movement of individuals as it pertains to their lifestyle. When considering the lifestyle of military personnel, i.e., occupational athletes, their requirements for fit-for-duty are at any given moment and may mean the difference between successful mission-completion and failure. Therefore, military warfighters must take into account the importance of nutrition as it relates to their physical and cognitive performances, both at work and home. The purpose of the following section is to provide basic nutritional facts and recommendations as they are applied to the military warfighter.

1.6.16. Whole Body Metabolism

To provide comprehensive nutritional recommendations, the topic's foundation begins with the fundamental explanation of whole-body energy metabolism. The body maintains energy balance by the application of Newton's First Law of Thermodynamics, i.e., energy can neither be created nor destroyed. Essentially, the body acquires energy input from nutritional sources, and then utilizes metabolic processes to convert the chemical energy to mechanical and thermal energy, as depicted in Figure 1.6.16-1. The body receives energy input from three major nutritional constituents – carbohydrates (CHO), proteins (PRO) and lipids (FAT) – and the energy stored is measured (i.e., kilocalories (kcal) or joules) by their complete metabolic combustion (Table 1.6.16-1).

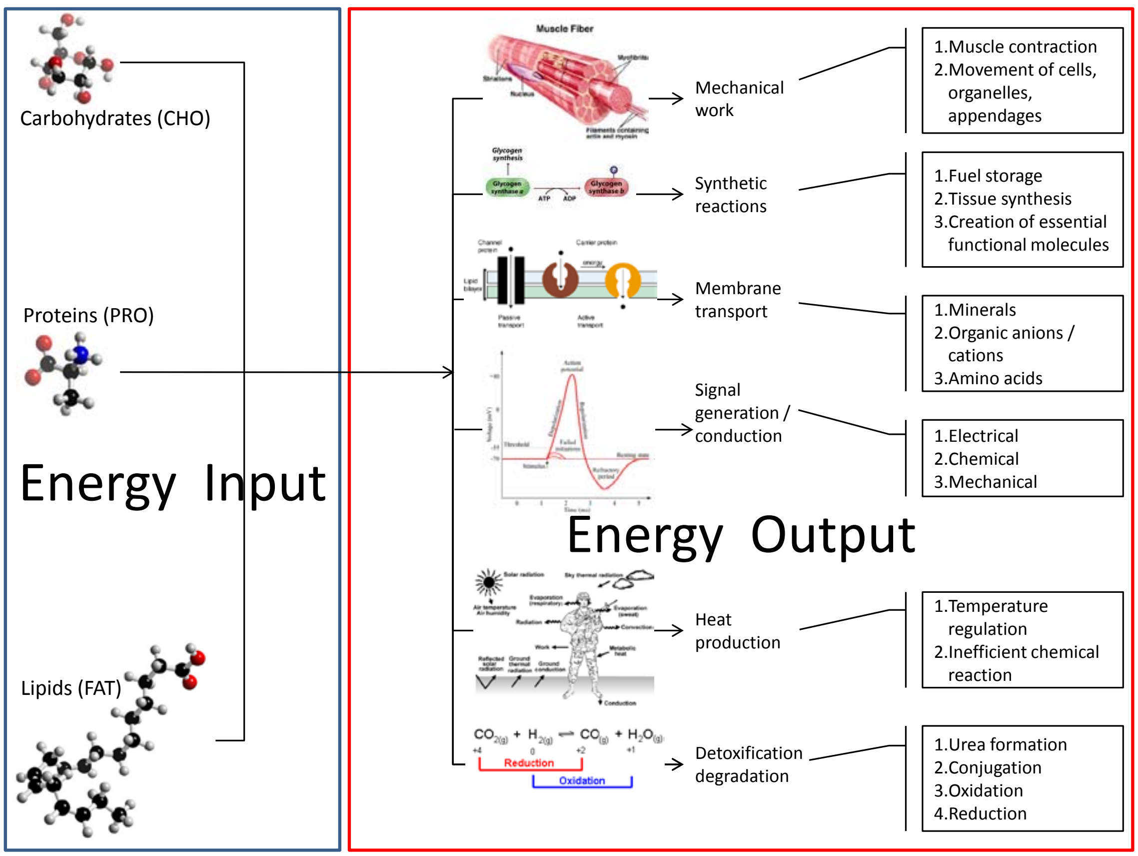

Figure 1.6.16-1. Overview of Whole Body Energy Metabolism

Table 1.6.16-1. Summary of Nutritional Source Metabolic Combustion

Nutritional Constituent	kcal $gram^{-1}$ (Produced)	liter O_2 $gram^{-1}$ (Used)	kcal liter O_2^{-1} (Produced)	Respiratory Quotient (RQ)
Carbohydrates (CHO)	4.2	0.84	5.0	1.00
Proteins (PRO)	4.3	0.96	4.5	0.80
Lipids (FAT)	9.4	2.00	4.7	0.70
Mixed Fuel	---	----	4.8	0.85

As these constituents (CHO, PRO and FAT) are metabolized through their respective metabolic pathways (i.e., glycolysis, gluconeogenesis, CHO & FAT oxidation), energy is given off (i.e., energy output) in several different forms: resting metabolic rate, diet-induced thermogenesis, nonshivering thermogenesis, and physical activity. An individual's resting metabolic rate (RMR), aka basal metabolic rate (BMR), represents the metabolic requirement of that particular body to maintain minimal aspects of life (e.g., generate/maintain ion gradients, signal transduction, respiratory and circulatory work, heat regulation, etc.) for a 24-hr period of time. Energy expenditure for RMR is measured in units of kcals or liters of O_2 and is approximately 20-25 kcal X kg of body $weight^{-1}$ or 0.2-0.25 L of O_2 X min^{-1} for the general adult human, respectively. The regression equations listed in Table 1.6.16-2 are accepted methods for estimating RMR in male and female adults.

Table 1.6.16-2. Validation of Harris-Benedict and Mifflin Equations for Resting Metabolic Rate in Obese and Nonobese People (from Frankenfield et al., 2003)

Gender	w = wt in kg	h = ht in cm	a = age in yr	MGF[a]
		Harris-Benedict		
Men	(13.75 x **w**) +	(5 x **h**) -	(6.76 x **a**) +	66
Women	(9.56 x **w**) +	(1.85 x **h**) -	(4.68 x **a**) +	655
		Mifflin		
Men	(10 x **w**) +	(6.25 x **h**) -	(5 x **a**) +	5
Women	(10 x **w**) +	(6.25 **h**) -	(5 x **a**) -	161

[a]Metabolic gender factor.

Generally, the central nervous and musculoskeletal systems account for 40% and 20% to 30% of RMR, respectively. Approximately 80% of inter-individual differences are accounted for by lean muscle mass, fat mass, age, and gender, leading to generalizations such as younger individuals have higher RMR than the elderly and women have a lower RMR than men. For average sedentary adults, RMR is about 60%-70% of their total daily energy expenditure (Fig. 1.6.17-2). Additional energy expenditures one might incur due to changing environmental conditions pertain to the energy cost of digesting food (i.e., diet-induced thermogenesis), metabolic production of heat (i.e., nonshivering thermogenesis), and any energy used for minor to major physical activity (i.e., fidgeting, manual labor, athletic performance, etc.) (Fig. 1.6.16-1). While diet-induced and nonshivering thermogenesis equal 5% to 15% of daily energy expenditure (DEE), the physical activity of daily life can be as great as 20% to 30%. Tables 1.6.16-3 and 1.6.16-4 are based upon general and specific activity exertion levels, respectively.

Table 1.6.16-3. Classification of Physical Activity Based upon Gender
(from McArdle et al., 2001)

Activity Level	kcal X min^{-1}	L O^2 X min^{-1}	mL O^2 X kg^{-1} X min^{-1}	METs[a]
Energy Expenditure, Women				
Light	1.5-3.4	0.30-0.69	5.4-12.5	1.2-2.7
Moderate	3.5-5.4	0.70-1.09	12.6-19.8	2.8-4.3
Heavy	5.5-7.4	1.10-1.49	19.9-27.1	4.4-5.9
Very Heavy	7.5-9.4	1.50-1.89	27.2-34.4	6.0-7.5
Energy Expenditure, Men				
Light	2.0-4.9	0.40-0.99	6.1-15.2	1.6-3.9
Moderate	5.0-7.4	1.00-1.49	15.3-22.9	4.0-5.9
Heavy	7.5-9.9	1.50-1.99	23.0-30.6	6.0-7.9
Very Heavy	10.0-12.4	2.00-2.49	30.7-38.3	8.9-9.9

[a]One MET = average resting oxygen consumption; L X min^{-1} based on 5 kcal per L of oxygen; mL X kg^{-1} based on 55-kg woman and 65-kg man.

Table 1.6.16-4 Energy Expenditures in Men (Based on 70-kg Male)

Activity Level	Activity	kcal X min^{-1}
A. Rest	Basal, aircraft pilots[a]	1.0
	Lying down fully relaxed[b]	1.2
	Basal, helicopter pilots[a]	1.2
	Rest KC-135 flight (experienced pilot)[c]	1.3
	Routine KC-135 flight (experienced pilot)[c]	1.5
	Piloting helicopters during aerobatics[a]	1.6
	Sitting in helicopter prior to engine start[a]	1.6
	Descent/landing helicopter[a]	1.7
	Sitting at rest[b]	1.7
	Seated in aircraft prior to engine start[a]	1.7
	Aerobatics by aircraft pilots[a]	1.8
	Emergency KC-135 flight (experienced pilot)[c]	1.9
B. Light Activity	4-G turns[d]	2.3
	Landing[d]	2.5
	Taxi for takeoff[d]	2.8
	Rolls[d]	3.0
	Takeoff[d]	3.2
	Takeoff by aircraft pilots[d]	3.2
	Barrel rolls[d]	3.6
	Slow walking[b]	3.8
	Walking (3.5 mph)[f]	4.7
	Aerial combat maneuvering[d]	4.8
C. Moderate Activity	Golf (walking & carrying clubs)[f]	5.5
	Gardening[b]	5.8
	Table tennis[b]	5.8
	Hovering in helicopter[a]	6.0
	Swimming (breaststroke, 1 mph)[b]	6.8
	Basketball[f]	7.3
	Chopping wood[f]	7.3
	Tennis[e]	7.6
D. Heavy Activity	Cycling at 10 mph, heavy bicycle[b]	8.9
	Basketball (recreational)[e]	9.7
	Bicycling (>10 mph)[f]	9.8
	Climbing stairs at 116 steps/min[b]	9.8
	Jogging, 5 mph[f]	9.8
E. Very Heavy Activity	X-country skiing[e]	10.0
	Jogging, 6.7 mph[e]	13.5
	Running (10 mph)[e]	17.8

[a]Littell & Joy (1969); average of measurements during flight in 3 different helicopters by the same 5 pilots or in utility aircraft (U-6A) by 4 pilots.
[b]Webb (1973).
[c]Kaufman et al. (1970).
[d]Harding (1987).
[e]Alpers et al. (1995).
[f]Thompson & Veneman (2005).

1.6.17. Macronutrients

As stated previously, the major energy input into the human body consists of nutritional constituents known as carbohydrates (CHO), proteins (PRO), and lipids (FAT). The energy provided by the chemical bonding between carbon (C),hydrogen (H), oxygen (O), and nitrogen (N) (note: found in protein) is insufficient to provide the body with the energy required to maintain itself and any additional physical activity required to sustain life. Therefore, it can be surmised that the chemical energy from CHO, PRO, and FAT is transferred to a more suitable energy source in the production of the high-energy molecule adenosine triphosphate (ATP). Energy in food molecular bonds is chemically released within our cells and then conserved in limited quantities in the form of ATP, which consists of adenosine (adenine + ribose) and three inorganic phosphate (Pi) groups. Carbohydrate provides about 4 kcal (16.7 kJ) of energy per gram compared to about 9 kcal (37.7 kJ) of energy per gram of FAT. However, CHO is more accessible. The rate of energy release is partially determined by the choice of the primary fuel source. The enzyme ATPase acts on ATP to split off a phosphate (Pi), rapidly releasing high energy (7.6 $kcal \cdot mole^{-1}$ of ATP). ATP is generated through three energy systems. The first two systems are anaerobic, energy is produced in the muscle cell without use of oxygen, and the latter system is aerobic, energy is produced in the muscle cell organelle, the mitochondria, with use of oxygen.

In the ATP-phosphocreatine system (i.e., ATP-PCr system), Pi is separated from phosphocreatine through the action of the enzyme creatine kinase. The Pi can then be combined with ADP to form ATP. This system is anaerobic, and its main function is to maintain ATP levels. The energy yield is 1 mole of ATP per 1 mole of PCr. During initial intense muscular activity, ATP is maintained as PCr declines as it is used to maintain ATP levels. However, after 3-15 s of maximal effort, ATP and PCr stores are depleted.

The glycolytic system involves the process of glycolysis, through which glucose or glycogen is broken down to pyruvic acid via glycolytic enzymes in the cytoplasm of the cells. When conducted without oxygen, the pyruvic acid is converted to lactic acid. Substrates for exercising muscle are glucose, available from blood glucose and liver glycogen, and muscle glycogen. To initiate glycolysis, muscle glycogen is broken down via glycogenolysis to glucose-1-phosphate and, in turn, to glucose-6-phosphate; glucose also converts to glucose-6-phosphate but at the cost of an ATP (one molecule of ATP per one molecule of glucose). One mole of glucose yields two moles of ATP, but one mole of glycogen yields three moles of ATP. The ATP-PCr and glycolytic systems are major contributors of energy during the early minutes of high-intensity exercise (the glycolytic system is limited to approximately 60-90 s in well-trained individuals). These anaerobic systems are limited in capacity, hence the term “anaerobic capacity” (whereas aerobic metabolism is measured as a rate).

The oxidative system is the primary means for energy production and involves breakdown of fuels with the aid of oxygen – this is true respiration or cellular respiration. This system yields more energy than the ATP-PCr or glycolytic system. Oxidation of carbohydrate involves: (1) glycolysis, (2) the Krebs cycle, and (3) the electron transport chain-oxidative phosphorylation. The latter two steps occur inside the cell organelles, the mitochondria, which in muscle are adjacent to the myofibrils and throughout the sarcoplasm. At the end of glycolysis, pyruvic acid converts to acetyl coenzyme A versus lactic acid in the anaerobic process. Acetyl CoA enters the Krebs cycle for oxidation and production of two moles of ATP. The remaining carbon (after

breakdown) combines with oxygen to form CO_2, which diffuses to the blood for transport to the lungs. Hydrogen from glycolysis and the Krebs cycle combines with coenzymes (NAD, nicotinamide adenine dinucleotide, and FAD, flavin adenine dinucleotide), which carry the hydrogen atoms to the electron transport chain where they are split into protons and electrons. The protons combine with oxygen to form water, and the electrons are transported through a series of reactions to provide energy for the phosphorylation of ADP to ATP. This process produces 39 molecules of ATP per molecule of glycogen (38 ATP per glucose); triglycerides from adipose cells and intramuscular fat deposits break down to glycerol and free fatty acids (FFA). FFA is released to the blood and diffuses into the muscle fibers for oxidation. Fat oxidation begins with beta (ß) oxidation of FFA and then follows the same latter path as carbohydrate oxidation: the Krebs cycle and the electron transport chain-oxidative phosphorylation. The energy yield for fat oxidation is much higher than for carbohydrate oxidation, and it varies with the FFA being oxidized. Although fat provides more kilocalories per gram than carbohydrate, fat oxidation requires more oxygen than carbohydrate oxidation. The energy yield from fat is 5.6 ATP molecules per oxygen molecule used compared to carbohydrate's yield of 6.3 ATP molecules per oxygen molecule. Oxygen delivery is limited by the oxygen transport system, so carbohydrate is the preferred fuel during high-intensity exercise. Protein oxidation is more complex because amino acids contain nitrogen, which cannot be oxidized. Protein contributes relatively little to energy production. Protein or fat can be converted to glucose via gluconeogenesis, and protein can be converted to fat via lipogenesis. Your muscles' oxidative capacity depends on their oxidative enzyme levels, their fiber-type composition, and oxygen availability. The following section provides basic information regarding the description, function, and storage of CHO, PRO, and FAT in the human body.

1.6.17.1 Carbohydrates. These hydrated carbon molecules (CH_2O), known as carbohydrates (CHO), are a major component of an individual's daily dietary intake (DDI). The most significant, biologically, of these sugars is glucose (Fig. 1.6.17-1) because of its central role in CHO metabolism. In fact, other CHOs are converted to glucose before being processed through CHO metabolic pathways. Interestingly, counterintuitive to their primary role in energy metabolism, CHOs are not the most abundantly stored energy source in the human body; approximately 0.6% (≈ 420 g) and 1% (≈ 1700 kcal) are stored relative to total body weight and total calories as depicted in Figure 1.6.17-2. In addition to serving as a primary energy source, these bio-molecules are significant structures in the body as glycoproteins, glycopeptides, and glycolipids, creating the fundamental building blocks in cell membrane collagen, nerve cell myelin, hormones, and hormone receptors.

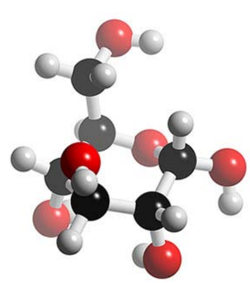

Figure 1.6.17-1. Glucose Structure

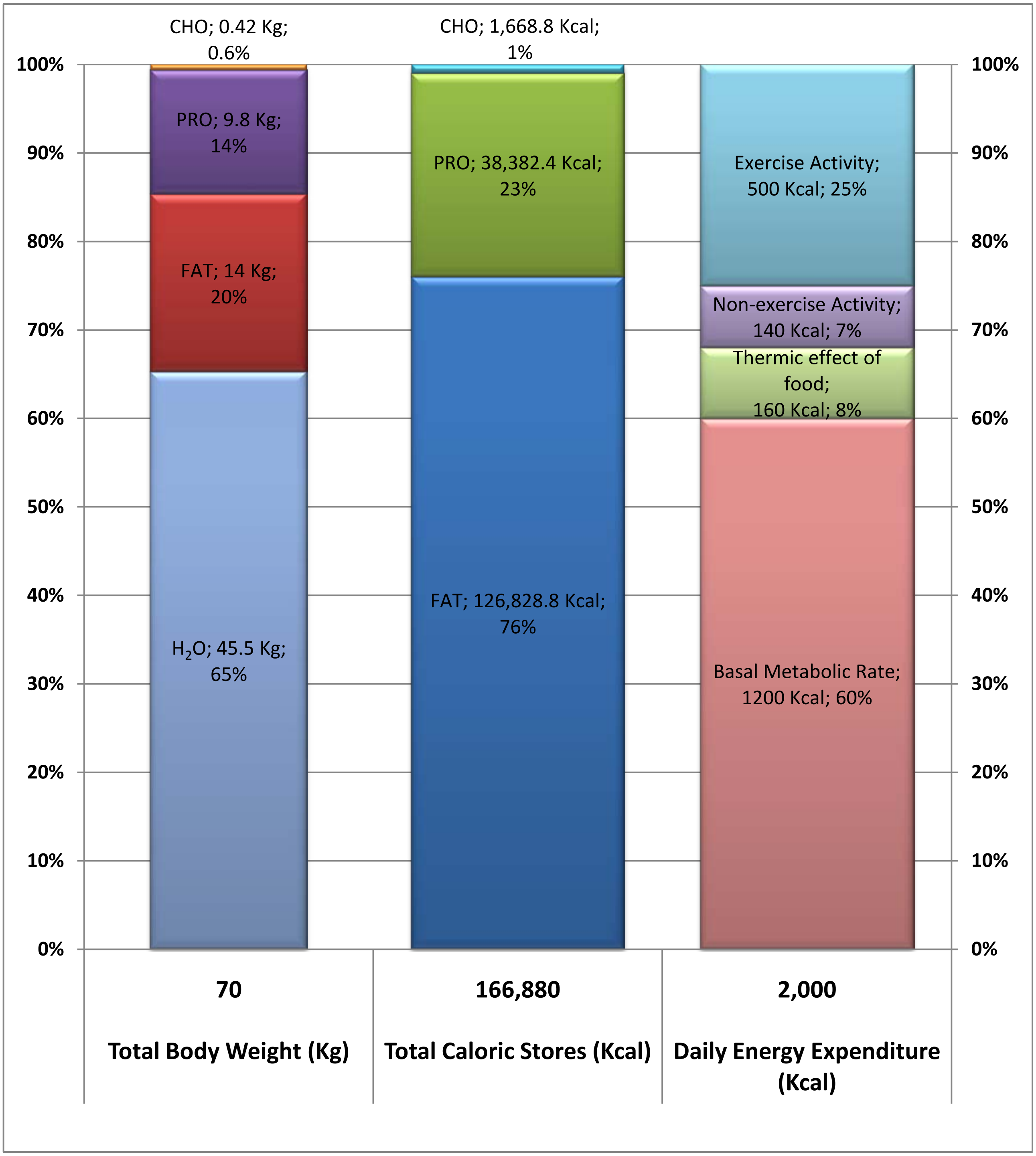

Figure 1.6.17-2. Composition of an Average 70-kg Individual

These sugars are commonly categorized into monosaccharides, disaccharides, and polysaccharides. Mono- (e.g., glucose, fructose, and galactose) and disaccharides (e.g., sucrose, maltose, and lactose) are the smallest of the sugar molecules, being a single- and double-chained sugar molecule, and are known as *simple sugars*. Polysaccharides are more than two monosaccharides chained together and are referred to as *complex carbohydrates*. Of primary interest with regard to human nutrition is *glycogen*, the polysaccharide that stores chained glucose molecules

together in the liver and muscle tissue. Within the body, approximately ¼ of the glycogen stores are in the liver, while the remaining ¾ is reserved for muscle tissue. The storage of liver glycogen equates to ≈ 75 to 100 g (≈ 300 to 400 kcal) of stored reserved to maintain blood glucose levels, while muscle glycogen can range from ≈ 300 to 400 g (≈ 1200 to 1600 kcal). The physiological significance of these respective glycogen stores focuses on the energy supply for the central nervous system (CNS), which is the brain and spinal cord, and the muscular system. Consider that the brain utilizes circulating blood glucose as its primary fuel source to produce energy to function. As shown in Figure 1.6.17-3, 75% of circulating blood glucose is derived from glycogen breakdown (i.e., glycogenolysis) to supply the brain energy for its metabolic function, which accounts for the majority of blood glucose utilization, 45%, thus the significance of maintaining blood glucose levels for optimal functionality.

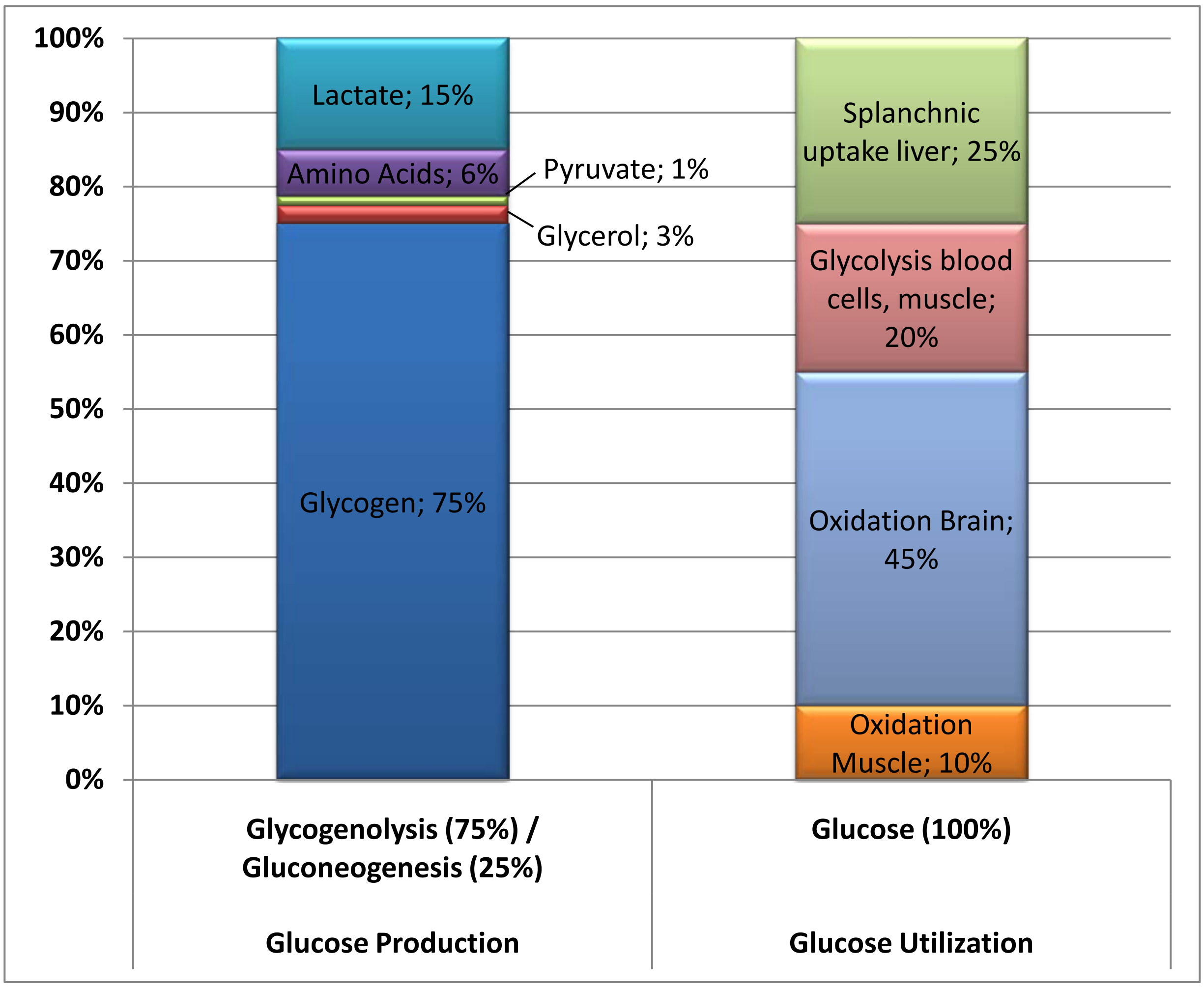

Figure 1.6.17-3. Quantitative Overview of Circulating Blood Glucose Turnover

Normal blood glucose ranges between 60 to 110 mg · dL^{-1}, with an average concentration of 80 mg · dL^{-1}; howeve,r after a meal glucose levels in the blood can rise as high as 120 to 140 mg · dL^{-1} but fall back within the normal range within 1 to 2 hr. Blood glucose is a highly regulated process, with the primary controllers being insulin and glucagon, wherein insulin is responsible for glucose uptake and glucagon releases glucose into the blood. The balance between uptake and release of glucose into the

circulating blood is to prevent two conditions from occurring: hyperglycemia and hypoglycemia. When blood glucose levels are allowed to climb higher than the normal range, the condition of hyperglycemia exists and can cause some serious pathological issues. If untreated, hyperglycemia can cause cellular dehydration, loss of glucose in the urine causing osmotic dieresis and the depletion of water and electrolytes, and tissue damage (e.g., vascular injury associated with uncontrolled diabetes mellitus increases the risk of heart attacks, strokes, renal disease, and glaucoma). The overall implications of hyperglycemia are an important aspect to health; the primary concern from an operational standpoint is the physiological effects of hypoglycemia on performance. With the low blood sugar of hypoglycemia, the brain succumbs to lack of fuel availability and reduced oxygen utilization, ultimately leading to neuroglycopenia (i.e., lack of glucose to fuel the brain) and autonomic neural stimulation. The manifestation of the condition is, of course, dependent upon the individual and his/her perception of the symptoms. The characterization of autonomic and neuroglycopenic symptoms can be grouped and characterized as in Table 1.6.17-1, but one should realize that there is not specific onset in the chronology of the symptoms; simply, an individual will consistently feel the same symptoms from episode to episode. The impact of hypoglycemia on performance and preventative recommendations will be discussed in further detail in the Nutrition and Performance area of this section.

Table 1.6.17-1. Classification of Hypoglycemic Signs and Symptoms Based upon Effector Groups

Autonomic Group	Neuroglycopenic Group
Feeling of warmth	Confusion or difficulty thinking
Nausea	Inability to concentrate
Pounding of the heart	Difficulty speaking
Sweating	Fatigue
Tingling	Headache
Trembling or shaking	Dizziness
	Tiredness
	Blurred vision
	Drowsiness
	Hunger
	Weakness

1.6.17.2 Protein. The significant role proteins (PRO) play in our daily dietary nourishment is reflected in the genesis of the word itself, *proteos – primary or taking first place*. The primary functional roles of PRO are as enzymes as biocatalysts in metabolic chemical reactions (e.g., phospofructokinase), peptide hormones in the regulation of growth and metabolism (e.g., insulin, somatotropin), structural proteins in the muscles and connective tissue (e.g., actin, myosin, collagen), transport proteins providing a method of movement for various substance (e.g., hemoglobin, albumin), and immunoproteins as antibodies (i.e., immunoglobins).

The human body is composed of approximately 14% PRO. Based upon the 70-kg body weight (BW) example (Fig. 1.6.17-2), the total PRO weight is 10 kg; 6 kg is considered to be metabolically active. The turnover, i.e., production rate vs. degradation rate, of the metabolically active PRO is estimated to be 3 to 5 g · kg of $BW^{-1} \cdot day^{-1}$

(Note: ≈ 1 lb of PRO for a 70-kg individual) and can account for 20% of an individual's BMR. Generally, PRO composition in humans simply consists of the same 20 amino acids (AA): 10 essential (EAA) and 10 nonessential (NEAA) (Table 1.6.17-2). An example of an animo acid is shown in Figure 1.6.17-4.

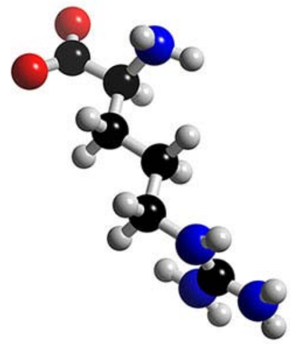

Figure 1.6.17-4. Arginine Structure

The *traditional* definition distinguishing the differences between EAA, (i.e., "*indispensable*") and NEAA (i.e., "*dispensable*") can be defined as those amino acids that must beconsumed exogenously and those that can be produced endogenously, respectively. The debate exists that amino acid categorization can be further broken down into nutrition, metabolic, and physiologic function when determining if they're essential, nonessential, or conditionally essential. That argument, however, is beyond the scope of the section; thus, the primary focus remains on the protein requirements for an individual.

Table 1.6.17-2. Classification of Essential and Nonessential Amino Acids

Essential Amino Acids		Nonessential Amino Acids	
Histidine	Phenylalanine	Arginine	Glutamine
Isoleucine	Threonine	Alanine	Glutamic Acid
Leucine	Tryptophan	Asparagine	Glycine
Lysine	Valine	Aspartic Acid	Proline
Methionine	Tyrosine	Cysteine	Serine

1.6.17.3 Lipids. Lipids, also known as FAT, exist in the human body in different forms: triglycerides, free fatty acids (FFA), phospholipids, and sterols. Contrary to popular belief, FATs are considered a vital aspect to dietary nourishment because of the diverse ways they are utilized physiologically: a primary energy source, as essential components of cell membranes and nerve fibers, support and protection of visceral organs, production of steroid hormones, mediator for fat-soluble vitamins, and thermoregulatory processes. FAT is composed of one glycerol molecule linked with three FFA, which most often will be either long chain, saturated (e.g., palmitic or stearic) or monounsaturated (e.g., oleic) fatty acids. FAT can be derived either endogenously or exogenously. In its most abundant form, triglycerides, FAT can be delivered to the body endogenously via hepatic and adipose lipogenesis or exogenously through dietary intake. Therefore, minimum requirements for dietary intake are not strict due to its relative social overabundance. However, 3% to 5% of FFAs cannot be synthesized endogenously and are known as essential free fatty acids

(EFFA) because they must be consumed through daily intake; those are the polyunsaturated fatty acids lenoleic, linolenic (Fig. 1.6.17-5), and arachidonic fatty acids.

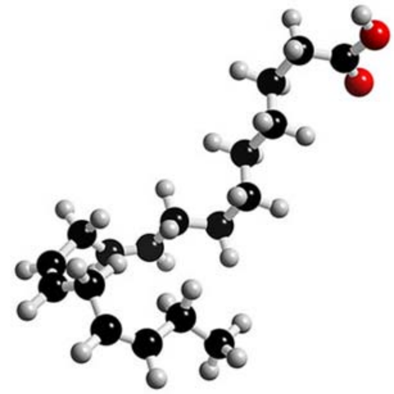

Figure 1.6.17-5. Linolenic Acid (ALA) Structure

Triglycerides constitute the majority of FAT in the body and are stored in adipose tissue, which is ≈ 20% of total body weight equating to ≈ 127,000 kcal of stored energy reserve in our ideal 70-kg individual (Fig. 1.6.17-2), making FAT the human body's most concentrated fuel reserve. The significance of FAT as a primary energy source is exemplified through the 70-kg individual's DEE distribution (Fig. 1.6.17-5). Of the 2,000 kcal required for total caloric DEE, the BMR relies on 70% of those calories being derived from FAT, in a rested state. In other words, in a seated, normal rested state your body utilizes FAT as the predominant fuel source. For this reason, FAT is considered an important aspect of nutritional intake to performance, and recommendations will be provided within the nutrition and performance section.

1.6.18. Nutrition and Performance

The first part of the preceding section introduced the idea of nutrition relative to an individual's needs, the concept of energy metabolism with regard to DEEs and DDIs, as well as the primary and secondary functions of the human body's energy sources. The intent of this section is to put into practical terms the applied aspect of nutrition with regard to the operational environment and the military personnel affected by mission demands. In doing so, recommendations for basic dietary daily intake for weight management and aspects of pre-mission/pre-competition meal planning for peak performance will be outlined. Although the section's language seems to be focused on athletic performance, one must remember that physiological stress can occur within the cockpit of an aircraft traveling at 400 kn on a hot day just as well as on the athletic field. Members of the United States Armed Services – Air Force, Army, Navy, Marines, and Coast Guard – must be considered nothing less than occupational athletes who are required to be in the best possible health and fitness, physiological and psychological, for them to have their peak performance at any given notice when duty calls.

1.6.18.1 Macronutrients. Before recommendations can be made regarding nutritional DDI , the first consideration should be to understand the bioenergetics of the metabolic pathways utilized and the energy source required to perform the work at peak performance. Metabolically, the energy systems to perform muscular work focus

on the phosphagen, glycolytic, and oxidative systems. Ultimately, each one is responsible for the production of the high-energy phosphate bond molecule ATP. Through metabolism, the human body takes the chemical of the macronutrients CHO, PRO, and FAT to create the more efficient, biologically active form of energy in ATP, which allows for a variety of work production; i.e., energy output (Fig. 1.6.16-1). There is only a small amount of ATP stored within the human body skeletal muscles, ≈ 5 mmol · kg wet weight, which only allows for a few seconds of work before more ATP is required. If the work being performed is short term, high intensity (i.e., ≈ 3 to 15 s), then the phosphagen system utilizes phosphocreatine (PCr) to resynthesize ATP rapidly; however, if the activity is to continue at the same intensity level, then the most probable outcome will be fatigue because of the lack of PCr availability. Yet, if the workload intensity were to decrease so as avoid fatigue and increase time of work duration (i.e., ≈ 60 to 180 s), then energy metabolism would transition into the glycolytic pathway, where glucose or glycogen (Fig. 1.6.16-4) is the primary fuel source in the production of ATP with the byproduct of lactic acid. Oxidative metabolic pathways, CHO and FAT oxidation, take primary control of energy production for activities longer than 3 min by oxidizing substrates such as glucose, muscle and liver glycogen, triglycerides (i.e., intramuscular, blood, and adipose tissue), along with negligible amounts of amino acids. Examples of activities for workloads that are considered short term, high intensity to long term, moderate intensity might range from performing an anti-G straining maneuver (i.e., AGSM) in a single bout (≈ 3 s), performing an F-16 qualification run at 9 G for 15 s, to flying offensive air combat maneuvers for a 1-hr-long sortie, respectively. The factors that determine the primary metabolic pathway of utilization are intensity, frequency, duration, volume, mode (or type of activity), sex, and current physical fitness status, as well as DDI and status of physiological energy reserves.

Optimal performance is based upon the balance of energy requirements, which is the balance between DDI versus DEE and the maintenance of optimal total body weight to include physiological energy reserves. If the balance is towards the negative, either due to insufficient DDI or an excessive DEE, these insufficiencies can lead to detrimental weight loss via fat or lean muscle mass or the depletion of vital glycogen stores. The losses of weight and energy reserves can be seen in poor performance in activities requiring strength and/or endurance and compromised immune, endocrine, or musculoskeletal functions. Avoidance of this energy requirement imbalance can be mitigated through the careful calculation of DEE components (Fig. 1.6.16-2) utilizing RMR calculations (Table 1-6-16-2) and physical activity energy expenditure estimates (Table 1.6.16-3 or Table 1.6.16-4) plus the complimentary DDI based upon recommendations from the American College of Sports Medicine’s joint position stand paper written by the American Dietetic Association and Dieticians of Canada, as well as the Dietary Guidelines for Americans 2005 published by the U.S. Department of Agriculture (USDA) and Department of Health and Human Services (HHS).

1.6.18.2 Carbohydrates (CHO). The recommendation for CHOs is based upon a conservative approach cautioning individuals not to solely base the CHO intake on a percentage range such as the one provided in the Dietary Guidelines for Americans 2005. The acceptable macronutrient distribution range (AMDR) for CHO is from 45% to 65% of DDI. Even though high CHO diets have been advocated in the past for athletes, the following examples show the pitfalls of that methodology. For example, when DDI is 4,000 to 5,000 kcal X d^{-1}, even a diet containing 50% of the energy from CHOs will provide 500 to 600 g of CHO (or approximately 7 to 8 g X kg^{-1} (3.2 to 3.6 g X lb^{-1}) for a 70-kg (154-lb) individual), an amount sufficient to maintain muscle glycogen stores from day to day. Conversely, when DDI is less than 2,000 kcal X d^{-1}, a diet providing 60% of the energy from CHO may not be sufficient to maintain optimal CHO reserves (4 to 5 g X kg^{-1} or 1.8 to 2.3 g X lb^{-1}) in a 60-kg (132-lb) individual. Therefore, a more appropriate range is from 6 to 10 g X kg^{-1} body weight X d^{-1} (2.7 to 4.5 g X lb^{-1} body weight X d^{-1}).

1.6.18.3 Protein (PRO). The same issue with CHO recommendation exists with PRO; for example, if PRO intake was 10% of DDI, total PRO ingestion (100 to 125 g X d^{-1}) could be greater than the recommended PRO intake for an individual. Currently, the PRO recommendation from the recommended daily allowance (RDA) is 0.8 g X kg^{-1} body weight and the USDA's AMDR is 10% to 35% of DDI. Albeit, the aforementioned PRO recommendation might be appropriate for a healthy adult ≥ 18 yr, it may fall short for individuals under extreme endurance or muscular strength workload demands. For those endurance individuals, an applicable range consists of 1.2 to 1.4 g X kg^{-1} X d^{-1}, while an individual needing high muscular strength might require more along the lines of 1.2 to 1.7 g X kg^{-1} X d^{-1}.

1.6.18.4 Lipids (FAT). As stated earlier in the section, FAT is an abundant macronutrient, and recommendations between agencies and professional organizations do not vary significantly. The DDI for FAT can be between 20% to 35%, with ≈ 10% derived from polyunsaturated, monounsaturated, and saturated FATS each.

1.6.18.5 Water. Water, i.e., H_2O, is not considered a macronutrient; however, as the most prevalent substance in the human body (Fig. 1.6.17-2), with ≈ 60% of the ideal 70-kg individual's total body weight being of water; it must be considered as being significant to biological function. A reflection of water's significance to physiological functions: it has been estimated that an individual can survive a loss of up to 40% of total body weight in CHO, PRO, and FAT, but a loss of 9% to 12% in total body weight in water can cause death.

During physical performance of activity, the human body will tend to lose water via sweat for a variety of reasons due to environmental conditions (i.e., ambient temperature, humidity, and wind), metabolic rate, elevated exertion levels, and clothing. As core temperature increases, the body will invoke its primary cooling effect and increase sweat rates in an attempt to cool itself. Thus, total body water losses increase, and concomitant electrolyte imbalances are induced, producing potentially poor performance and health issues (e.g., heat exhaustion, heat stroke, muscle cramps, rhabdomyolysis, acute renal failure, exercise-induced hyponatremia).

Prevention is the key; for an individual to prevent dehydration, one must know what euhydration is relative to the body. Hydration assessments consist of establishing a first-morning average body weight baseline value, then monitoring urine and body

weight movements to calculate sweat losses and H_2O replacement needs or employing a urine specific gravity (USG) test to determine euhydration. The next best step in preventing or minimizing the further progression of a dehydrated state is to recognize the signs and symptoms of dehydration listed below as adapted from the American College of Sports Medicine's Position Stand on Exercise and Fluid Replacement:

- Dehydration increases physiologic strain and perceived effort to perform the same exercise task and is accentuated in warm-hot weather.
- Dehydration can increase the likelihood or severity of acute renal failure consequent to exertional rhabdomyolysis.
- Dehydration and sodium deficits are associated with skeletal muscle cramps.
- Symptomatic exercise-associated hyponatremia can occur in endurance events.
- Fluid consumption that exceeds sweating rate is the primary factor leading to exercise-associated hyponatremia.
- Large sweat sodium losses and small body weight (and total body water) can contribute to exercise-associated hyponatremia.
- The greater the dehydration level, the greater the physiologic strain and aerobic exercise performance decrement.
- Critical water deficit and magnitude of exercise performance degradation are related to the heat stress, exercise task, and the individual's unique biological characteristics.
- Dehydration (>2% BW) can degrade aerobic exercise performance, especially in warm-hot weather.
- Dehydration (>2% BW) might degrade mental/cognitive performance.
- Dehydration (3% BW) has marginal influence on degrading aerobic exercise performance when cold stress is present.
- Dehydration (3% to 5% BW) does not degrade either anaerobic performance or muscular strength.
- Hyperhydration can be achieved by several strategies but has equivocal benefits and several disadvantages.
- Dehydration is a risk factor for both heat exhaustion and exertional heat stroke.

Finally, the knowledge of modifying factors that affect how an individual responds to a dehydrated status might be the difference between prevention and a mishap. The modifying factors of dehydration can be grouped into three categories: age, sex, and nutrition. The considerations with age focus upon older adults and children; older adults are prone to age-related, decreased thirst sensitivity when dehydrated and slower renal responses to water, predisposing them to slower voluntary reestablishment of euhydration and increased risk of hyponatremia, respectively. While on the other end of the spectrum, prepubescent children have lower sweat rates than adults, in turn making thermoregulation more difficult in environmental conditions in which adults can acclimatize. Generally, women have lower sweat rates than men and are at greater risk for developing symptomatic hyponatremia, but the etiology is not related to renal water and electrolyte retention. Every effort should be made to promote euhydration before dehydration occurs, and one of the better way to do so is through meal consumption; eating not only promotes water intake but also sodium and potassium electrolyte replenishment. The diuretic effects of caffeine and alcohol are a concern, but only in so much as how much and when they are consumed. Caffeine

consumption below < 180 mg · dL^{-1} is not likely to increase daily urine output beyond the normal daily excretion or contribute to dehydration, unlike alcohol, which is a strong diuretic and should be only consumed during the post-activity meal.

1.6.19. Meal Planning

As the final aspect of nutritional recommendations, the topic of meal planning is of significance. The reasons for meal planning are quite simple: understand the basic concept of whole body metabolism and bioenergetics in the human body, identify and explain the function of the three main fuels source we use to create energy, make certain DDI and DEE are matched for optimal weight management, and reensure that fuel energy reserves are properly stored with complete fuel reserves to avoid the deleterious effects of hypoglycemia and dehydration on physical and cognitive performances. Regardless of whether or not the military warfighter is on the ground, in the air, or on the sea, the practical application of nutrition and performance affect everyone. From the pilots of tankers to fighters to reconnaissance; to the flight surgeons, nurses and technicians of the critical care aeromedical transport (CCAT) teams; to the high altitude parachutists, combat rescue officers, and special operation personnel; they all must be have nutritional awareness. An awareness of one's nutrition entails the fundamental building blocks of meal planning for mission readiness and preparedness and consists of the following core questions; ***what***, ***when***, ***where***, ***why***, and ***how***.

1.6.19.1 Pre-Activity Meal Planning. An individual should approach pre-activity planning with a thoughtful focus on those core questions from an anticipatory perspective. Before activity, a meal or snack should provide sufficient fluid to maintain hydration, be relatively low in fat and fiber to facilitate gastric emptying and minimize gastrointestinal distress, be relatively high in carbohydrate to maximize maintenance of blood glucose, be moderate in protein, be composed of familiar foods, and be well tolerated by the individual. The size and timing of the pre-activity meal have an important relationship because most individuals don't like to perform work on a full stomach; thus, a smaller meal would be consumed near the event to allow for gastric emptying, whereas larger meals can be consumed when more time is available. Certain amounts of CHO supplementation, ranging from ≈ 200 to 300 g of CHO for meals consumed 3-4 hr before the activity/work to be performed, have been shown to enhance performance. Although the above guidelines are effective, individual needs must be emphasized; individuals can know what works best for them by experimenting with new foods and drinks prior to and during practice events and planning ahead to ensure they will have access to these foods at the appropriate time. As far as pre-activity hydration, the individual should drink approximately 5 to 7 mL X kg^{-1} body weight (≈ 2 to 3 mL X lb^{-1}) of water or a sport beverage at least 4 hr before exercise, allowing enough time to optimize hydration status and for excretion of any excess fluid as urine. If the individual doesn't produce urine, or the urine is dark or highly concentrated, he/she should slowly consume more fluid (e.g., ≈ 3 to 5 mL X kg^{-1}) about 2 hr before the event.

1.6.19.2 During-Activity Meal Planning. During exercise, the primary goals for nutrient consumption are to replace fluid losses and provide CHO, ≈ 30 to 60 g X h^{-1} for maintenance of blood glucose levels. These nutrition guidelines are especially

important for endurance events lasting longer than an hour when the individual has not consumed adequate DDI before the activity, especially when considering the activity is taking place in an extreme environment (i.e., heat, cold, or high altitude). CHO intake should begin shortly after the onset of activity; consuming a given amount of CHO after 2 hr of exercise is not as effective as consuming the same amount in 15- to 20-min intervals throughout the entire duration. The purpose for drinking during exercise is to avoid a H_2O debt >2% of body weight; thus, for optimal fluid replacement the individual needs to consider sweat rate, the duration, and opportunities to drink. The type, intensity, and duration of exercise and environmental conditions will alter the need for fluids and electrolytes. Additionally, drinks containing electrolytes, such as sodium and potassium, help to replace sweat electrolyte losses, whereas sodium stimulates thirst and fluid retention and CHO provides energy. The optimal fluid replacement drink should contain 6% to 8% CHO for activities lasting longer than 1 hr.

1.6.19.3 Post-Activity Meal Planning. After exercise, the nutritional goal should be to provide fluids, electrolytes, and CHOs to replace muscle glycogen, ensuring optimal recovery. The when (i.e., timing) and what (i.e., composition) of the post-activity food intake is dependent upon the intensity and duration of the workload performed (i.e., did glycogen depletion occur) and on when the next intense work will occur. For optimal glycogen resynthesis, the post-activity CHO ingestion should be ≈ 1.0 to 1.5 g X kg^{-1} body weight (0.5 to 0.7 g X· lb^{-1}) during the first 30 min and again every 2 hr for 4 to 6 hr. PRO can be provided after exertional work to provide amino acids for repair of muscle tissue. Also, the type of carbohydrate consumed affects post-activity glycogen resynthesis; glucose and sucrose are both effective, and CHO intake of high glycemic index provides higher muscle glycogen levels 24 hr post-activity. Because most individuals don't consume enough fluids during physically demanding activity to balance fluid losses, the session is completed with them in a dehydrated state. If adequate time is taken, intake of normal DDI will restore hydration status by replacing fluids and electrolytes lost during the activity. However, a more rapid and complete recovery from excessive dehydration can be accomplished by consuming ≈ 16 to 24 oz of fluid · lb^{-1} of body weight lost during the activity.

1.6.20. Special Considerations

- Current Physiological Status
- Environmental Conditions
  - Hot and humid environments
  - Cold environments
  - Altitude
- Mission Requirements

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Concepts

Energy metabolism

Vocabulary

Basal metabolic rate (BMR)
Blood glucose
Dehydration
Energy expenditure
Macronutrients
Physical activity
Resting metabolic rate (RMR)
Water

1.7. Thermal Effects

Capt Mark White, USAF, BSC

1.7.1. Thermal Stress

1.7.1.1 Introduction. Mission requirements impose a variety of threats to military personnel in the operational environment, thermal stress being one of significance. The operational environment can range greatly and subject personnel to a variety of environmental extremes, such as cold and hot exposure. For example, you might find yourself at the Yuma Proving Grounds, AZ, and exposed to heat stress on the ground while waiting to board an aircraft for High Altitude Low Opening (HALO) school, with the ambient temperature at 40°C (104°F). Then, within minutes you're flying at 20,000 ft MSL in an unpressurized cabin and the temperature is now a cool 0°C (32°F). One minute you're sweating it out on the flight line preparing for a jump and the next minute the sweat begins to turn ice-cold as the ramp opens and a 20-mph gust of wind drops the ambient temperature to a wind chill blown -8°C (17°F). Another scenario to consider: an F-15 pilot stationed at Elmendorf AFB, AK, is well versed on the aircraft's life support and environmental control systems, which allow pilots the comfort of flying with minimal interference from the outside world. However, if the heater control core unit shorts out and the cockpit temperature equalizes with the ambient conditions while being more than 2 hr away from landing, normal cold weather flying attire may be inadequate. Regardless of the situational circumstances, the environment of a closed cabin can pose similar thermal stress to the crew who are ill-prepared for changes encountered with altitude. The following section focuses on the human body's capacity to maintain physiological and psychological function under thermal stress of heat and cold exposure. A solid understanding of the physical and cognitive changes and protective defense strategies can provide potentially life-saving guidelines to air and ground crew faced with an environment that challenges human performance.

1.7.1.2 Biophysics of Environmental Stressors. For the human body to maintain homeostatic balance, it must manage internal systems based upon the input of external stressors. Examples of **external stressors** considered to be a threat to the human body include thermal stressors (i.e., heat, cold), odor, food, water, hypoxia, noise, light, darkness, trauma or injury, electricity, physical threats, and bacteria or viruses. With exposure to **thermal stressors**, the human body must maintain the **core body temperature (T_C)** through the balance of heat gain and heat loss (Fig. 1.7.1-1). If the rate of heat production (i.e., environmental, metabolic, hormonal, or food thermogenesis) is greater than the rate of heat debt, then the net is a **heat gain** and the positive heat storage results in **hyperthermia**. Conversely, if heat loss (i.e., through conduction, convection, radiation, and evaporation) is greater than heat gain, then the net is **heat loss** and the negative heat storage results in **hypothermia**.

The **balance of heat storage**, shown in Figure 1.7.1-1, can be mathematically expressed as follows;

$$S = M - (\pm W) - E \pm (R + C) \pm K$$

where **S** = storage of heat, **M** = metabolic heat, **W** = work, **E** = evaporation, **R** = radiation, **C** = convection, and **K** = conduction.

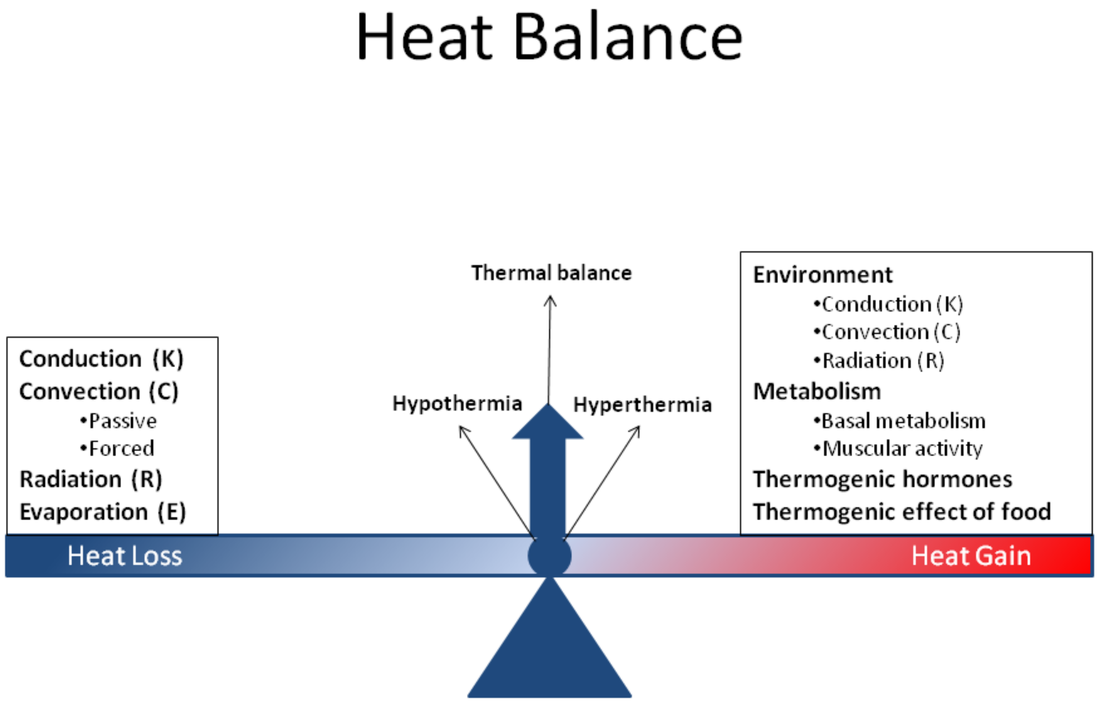

Figure 1.7.1-1. Balance of Heat Storage (Tipton, 2006)

The transfer of heat between the body and the environment occurs through **conduction**, **convection**, **radiation,** or **evaporation** as shown in Figure 1.7.1-2. **Environmental factors** that affect the rate of heat exchange consist of **air temperature**, **air movement (wind)**, **air saturation (humidity)**, and **water immersion (submersion)**; each of these will be addressed in further detail under hot and cold stressor sections as they relate to thermoregulation. **Conduction** is defined as the transfer of heat to or from one object to another, e.g., by direct contact with an external object or, within the body, through tissue-to-tissue, all of which occur due to a temperature gradient. The heat loss of a person in a resting state at normal room temperature is approximately 3%. The movement of heat to or from air or water across the body due to thermal currents, body-in-motion, and/or air (i.e., wind chill) or water (i.e., current) movement is **convection**. The primary source of heat loss, transferring heat out and away from the core body, is through convection and can account for approximately 12% of heat loss under normal room temperatures. Heat loss or gain occurs when the body is surrounded by air or water that is lower or higher in temperature than the body, thus the transfer of heat down the gradient. The loss of heat will be greatly increased if the air or water surrounding the body is of a turbulent nature; i.e., wind chill or turbulent current or flow of water. Conversely, **radiation** from heat exchange is independent of air movement and occurs with the radiant temperatures of solar, sky, large objects, and ground either being higher or lower than

the body; thus, the body will gain heat or lose heat to the environment. **Evaporation**, the most important method the human body uses for thermoregulation, consists of the transfer of heat from the body when sweat accumulates on the skin and evaporates into the air. Under normal room temperatures in a rested state, evaporation can be responsible for up to 25% of heat loss. As evaporation occurs, the heat transferred from the absorption of sweat is called the latent heat of evaporation and equals approximately 0.58 kcal/g of water absorbed. Under environmental conditions in which heat loss from the body is hindered, it is critical to understand that core body temperature may increase 0.2°C/min during moderate activity levels, which may cause thermal injury within 15-20 min.

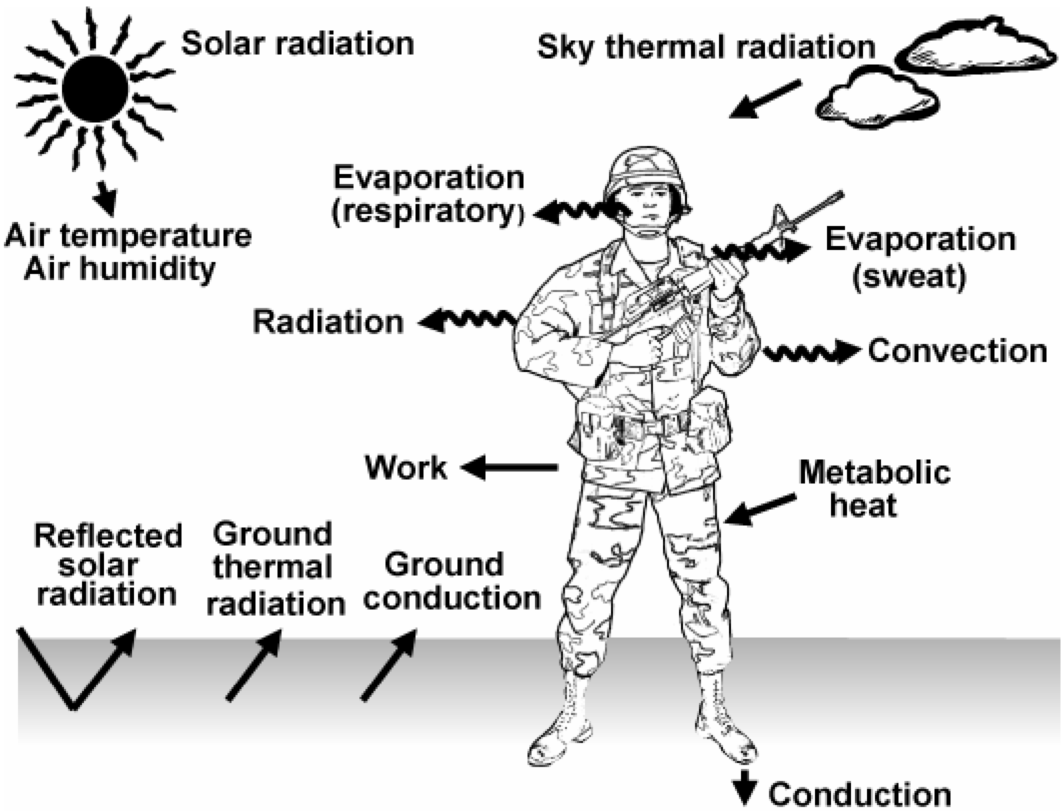

Figure 1.7.1-2. Biophysics of Heat Exchange (TBMED507, 2003)

1.7.1.3 Thermoregulation of Normal Body Temperature. From a biological perspective, the human body's ability to maintain constancy of body temperature places us in a group of advanced animals called **homeotherms**, along with monkeys, dogs, bears, and birds. The homeothermic ability, that is the ability to function relatively independent of the environment because of the maintenance of the T_C, has allowed us to perform in extreme environments (Table 1.7.1-1). The constancy of T_C is of physiological significance, as other biological processes are temperature dependent. For example, impairment of oxygen transport, cellular metabolism, muscle contractions, and neural function might mean the difference between life and death when considering the overall performance of the human body.

Table 1.7.1-1. Relationship of Environmental and Core Body Temperatures

Environmental Temperature (°C)		Core Body Temperature (T_C) (°C)	
Very hot sauna	100	44	Upper limits for survival
	90		Impaired thermoregulation
Sand temperature, Sudan	80	42	Heat stroke, brain damage
	70		
Potable coffee	60	40	Extreme physical exercise and fever
Death Valley, July	50		
Hot bath	40	38	
Mean July temp, Yuma, AZ	30		Normal range
Cool bath	20	36	
	10		Intense shivering and impaired coordination
Mean Jan temp, NYC, NY	0	34	
	-10		Violent shivering; speech and thought impaired
Mean Jan temp, Fairbanks, AK	-20	32	
	-30		Decreased shivering; erratic movements; incoherent
Mean Feb temp, South Pole Station	-40	30	
	-50		Muscular rigidity; semiconscious
Mean July temp, South Pole Station	-60	28	
	-70		
	-80	26	Unconscious; cardiac arrhythmias
	-90		Thermoregulation absent
	-100	24	
		22	

The term "**normal body temperature**" is one that is not easily defined because there can be minor individual variations in one's body temperature, especially when it's measured in different areas of the body or under different circumstances. Normal body temperature ranges from 36.0°C to 37.5°C (96.8°F to 99.5°F), with the commonly known average temperature reading of 36.7°C to 37.0°C (98.0°F to 98.6°F), and can maintain function within the limits of 36.0°C (NOTE: experienced in the early morning sleep cycle) and 40°C (NOTE: may occur during maximal exercise). Although there can be considerable variability in temperatures throughout the body, it's the core temperature that maintains constancy and is usually defined as the temperature of the hypothalamus, the primary temperature regulator (Figure 1.7.1-3).

The **hypothalamus** is known as the thermostat of the body, as one of its primary functions is to monitor the temperature of the body and then manage the physiological response. As the primary control center, the hypothalamus relies upon sensory input from **thermoreceptors** located throughout the body. Thermoreceptors can be categorized as central or peripheral, central being that of the anterior and posterior hypothalamus as well as the preoptic region, while the peripheral receptors consist of

the nervous, vascular, and muscular systems and the abdominal cavity. Of the peripheral receptors, a small portion exists in the nerves, abdomen, and deep leg muscles and veins, while the greatest density is in the skin. However, the central thermoreceptors are the most important for core temperature regulation.

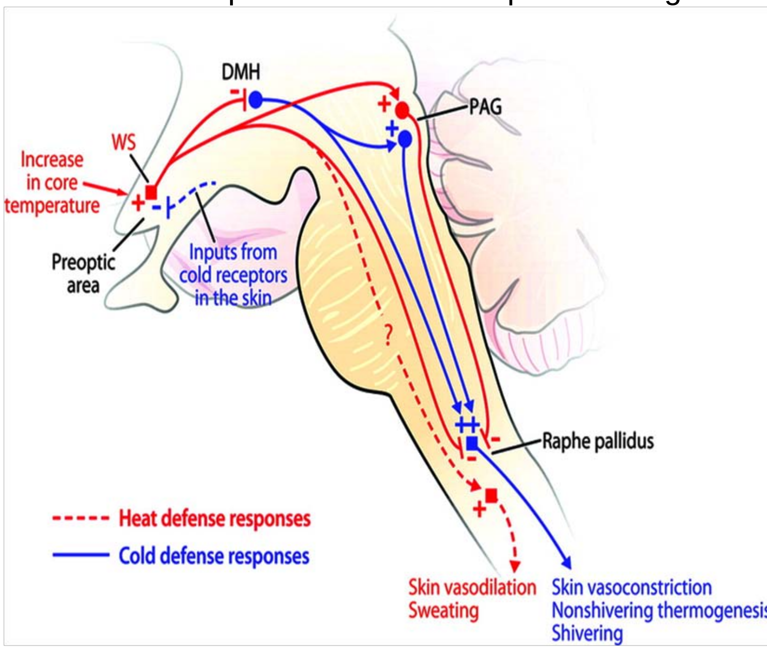

Figure 1.7.1-3. Thermoregulatory Center of the Brain; Anterior and Posterior Hypothalamus and Preoptic Area (http://www.neurology.org/cgi/content/full/69/12/1293/F116)

The hypothalamus is responsible for **dual regulation** of **hot and cold defense responses**; thus, the response of the hypothalamus is dependent upon the thermoreceptor input (Fig. 1.7.1-3). The anterior and preoptic areas of the hypothalamus are coupled with the posterior hypothalamus in a negative feedback loop inhibitor response. The heat defense response is initiated when the anterior hypothalamus and preoptic area are stimulated by local temperature changes in heat; especially in the blood where temperature changes of less than 0.01°C (0.018°F) can elicit a reaction. The heat defense response consists of the evaporative heat loss mechanism (i.e., stimulation of sweat glands), inhibition of the cardiovascular control center normal vasoconstrictor vascular tone to the skin (i.e., skin vasodilation), and inhibition of thermogenesis (i.e., shivering and metabolic rate). Conversely, when the peripheral thermoreceptors, primarily the skin, provide afferent input into the posterior hypothalamus, the cold defense response is stimulated, which inhibits the heat defense response. Thus, the heat loss mechanism is inhibited and vasoconstriction occurs in skin vasculature due to the stimulation of the cardiovascular control center (i.e., blood is shunted away from the periphery and redirected to the core thoracic/abdominal area). In addition, the stimulation of shivering and metabolic thermogenesis increase insulative factors and heat production. As a result of stimulation of the posterior hypothalamus, epinephrine and norepinephrine (other contributors to metabolic thermogenesis) are directly secreted and thyroxin production is indirectly increased due to an increase secretion of thyrotropin-releasing factor, which stimulates the secretion of thyrotropin from the pituitary gland. Albeit, the hypothalamus is responsible for the primary regulation of the physiological response, there is another response defense mechanism that aids in thermoregulation: human behavior. A factor easily overlooked,

the human behavior response to hot or cold exposures is of significance when considering the defense mechanisms of thermoregulation. In an extreme cold environment, one might consider adding additional layers of clothing, or moving under shelter; on the other hand, excessive heat might drive one to drink fluids, reduce clothing layers, reduce physical activity, and seek shade. Regardless of the environment, it's both the physiological and behavioral response mechanisms that allow the human body's homeothermic abilities to maintain core temperature constant under extreme conditions, especially those that are imposed upon our military personnel.

Mission requirements impose a variety of threats to military personnel in the operational environment, thermal stress being one of significance. But the environment of a closed cabin can pose similar thermal stress to the crew who are ill prepared for changes encountered with altitude

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Concepts

- Balance of heat storage
- Cold defense response
- Dual regulation
- External stressors
- Heat gain / loss
- Hot defense response
- Normal body temperature
- Thermoregulation

Vocabulary

- Air movement
- Air saturation
- Conduction
- Convection
- Core body temperature (T_C)
- Evaporation
- Homeotherm
- Hyperthermia / Hypothermia
- Hypothalamus
- Thermal stressors
- Thermoreceptors
- Water immersion

1.7.2. Heat Stress

"As part of a crew member in a deployed environment you are constantly counseled on the negative effects of dehydration and performance, and the idea of euhydration has been reiterated to the point that every drink you take is preventative and you're not going to be the one that succumbs to the hot environment. You've been hydrating since the night before. In the hot preflight environment, you continue to hydrate but begin to develop a headache. During the first low level route the headache gets worse, but you decide not to mention it; the mission comes first, so let's press. At the end of route you self-identify as having some sort of dehydration or heat-related problem. The crew performs a full stop of the aircraft and declares a ground emergency for medical attention. The ambulance is called and you are checked out on the aircraft. You feel good enough to get yourself to the doctor, so you decline transportation to the hospital and are on your way to flight medicine, exactly where you didn't want to end up. The flight doctor performs a blood test and discovers that you're well hydrated but your electrolytes have been almost completely depleted. The solution is simple: you receive an IV solution to replenish your electrolytes and are released back to duty. Your instructions are to eat a balanced diet which is meant to maintain electrolytes. Because of you there's a new squadron policy; it has changed supplemental water procedures to include a performance drink during hot temperatures to aid in maintaining electrolytes...."

1.7.2.1 Introduction. For the human body to maintain homeostatic balance, it must manage internal systems based upon the input of external stressors. External stressors considered to be a threat to the human body include thermal stressors (i.e., heat, cold), odor, food, water, hypoxia, noise, light, darkness, trauma or injury, electricity, physical threats, and bacteria or viruses. With exposure to thermal stress, the human body must maintain its core body temperature (T_C) through the management of heat loss and heat gain. The body will either dissipate or gain heat through **convection**, **evaporation**, **conduction,** or **radiation** and generate heat through metabolism, shivering, or physical activity as shown in Figures 1.7.1-1 and 1.7.1-2. When considering the thermal stress of **heat gain**, there are four significant environmental variables that must be considered: **air temperature**, **air movement (wind speed)**, **air saturation (humidity)**, and **radiant heat (solar, sky, and ground)** (Fig. 1.7.1-2).

Relative Humidity (%)

Heat Index (Apparent Temperature)

Air Temperature °F	40	45	50	55	60	65	70	75	80	85	90	95	100
110	136												
108	130	137											
106	124	130	137										
104	119	124	131	137									
102	114	119	124	130	137								
100	109	114	118	124	129	136							
98	105	109	113	117	123	128	134						
96	101	104	108	112	116	121	126	132					
94	97	100	103	106	110	114	119	124	129	135			
92	94	96	99	101	105	108	112	116	121	126	131		
90	91	93	95	97	100	103	106	109	113	117	122	127	132
88	88	89	91	93	95	98	100	103	106	110	113	117	121
86	85	87	88	89	91	93	95	97	100	102	105	108	112
84	83	84	85	86	88	89	90	92	94	96	98	100	103
82	81	82	83	84	84	85	86	88	89	90	91	93	95
80	80	80	81	81	82	82	83	84	84	85	86	86	87

With Prolonged Exposure and/or Physical Activity

Extreme Danger	Heat stroke or sunstroke highly likely
Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely
Extreme Caution	Sunstroke, muscle cramps, and/or heat exhaustion possible
Caution	Fatigue possible

Figure 1.7.2-1. National Weather Service Heat Index Chart

Heat stress occurs when the balance of heat exchange between the environment and the human body favors heat gain, with the ultimate result being an increase in core body temperature (T_C). The physiological and behavioral effects of heat stress are referred to as heat strain. The environmental factors that greatly influence heat stress are high air temperature, high humidity, high radiation heat, and low air movement. The National Weather Service's **Heat Index Chart** stratifies the risk of heat stress over time of exposure relative to air temperature plus humidity, as shown in Figure 1.7.2-1. The U.S. Army utilizes a heat stress index, called the **wet bulb globe temperature (WBGT),** that provides strategic guidelines to maximize human performance by quantifying physical activity exertion levels, work/rest ratios for times of exposure, and fluid replacement based upon air temperature, humidity, and air movement (Table 1.7.2-1). The U.S. Air Force employs the **fighter index of thermal stress (FITS)**, as outlined in AFPAM48-151, 18 November 2002, that represents cockpit heat stress stratified across zones of risk; the FITS zones are called the caution and danger zones (Table 1.7.2-2). The FITS caution zone (32°C to 38°C) instructions for implementation consist of (1) be alert for heat stress, (2) drink plenty of noncaffeinated fluids, (3) avoid exercise 4 hr prior to takeoff, and (4) limit ground operations to 90 min outside of an air-conditioned environment. The FITS danger zone (> 38°C) adds the following five instructions to the four instructions of the caution zone: (1) minimum recovery time, landing time to next take off between flights, is 2 hr; (2) limit ground operations to 45 min for fighter/trainer aircraft types and time outside air-conditioned environment; (3) if possible, wait in a cool, shaded area if the aircraft is not ready to fly; (4) complete a maximum of two aircraft inspections, two exterior inspections on initial sorties, and one exterior inspection on subsequent sorties for fighters and trainers; and (5) Undergraduate Flying Training solo students are to complete one exterior aircraft inspection per sortie.

Table 1.7.2-1. Wet Bulb Globe Temperature Heat Stress Index

Heat Stress Card

Fluid Replacement Guidelines for Warm Weather Training Conditions

Acclimated after approx. two weeks training wearing BDU, hot weather

High Risk for Heat Illness:
(The more factors, the higher the risk)

- **Not acclimatized** to heat (need 10-14 days to get trainees adequately acclimated)
- Poor fitness
- Exceeds Body Fat Standard
- Cumulative inadequate hydration (day to day)
- Minor illness (cold symptoms, sore throat, low grade fever)
- Taking drugs/supplements/dietary aids
  Ex: Allergy or cold remedies
  Ephedra supplement
- Use of alcohol in the last 24 hours
- Prior history of heat illness (any heat stroke, or >2 episodes of heat exhaustion)
- Skin disorders such as heat rash and sun burn which prevent effective sweating
- Age > 40 years

Do:

Maintain the buddy system to look out for each other.

Observe soldiers drinking water in required amounts not to exceed 1½ quarts per hour or 12 quarts per day.

Ensure adherence to work rest cycle in heat categories.

Ensure soldiers are well hydrated before starting hard work.

Ensure soldiers have adequate time to eat and drink.

Encourage soldiers to eat all meals for needed salts.

Easy Work	Moderate Work	Hard Work
• Weapon Maintenance • Walking Hard Surface at 2.5 mph, < 30 lb Load • Marksmanship Training • Drill and Ceremony	• Walking Loose Sand at 2.5 mph, No Load • Walking Hard Surface at 3.5 mph, < 40 lb Load • Calisthenics • Patrolling • Individual Movement Techniques, i.e. Low Crawl, High Crawl, etc.	• Walking Hard Surface at 3.5 mph, ≥ 40 lb Load • Walking Loose Sand at 2.5 mph with Load • Field Assaults

- The work-rest times and fluid replacement volumes will sustain performance and hydration for at least 4 hours of work in the specified heat category. Fluid needs can vary based on individual differences (± ¼ qt/h) and exposure to full sun or full shade (± ¼ qt/h).
- **NL** = no limit to work time per hour.
- **Rest** means minimal physical activity (sitting or standing), accomplished in shade if possible.
- ***CAUTION: Hourly fluid intake should not exceed 1½ quarts.***

  Daily fluid intake should not exceed 12 quarts.
- If wearing body armor add **5°F** to WBGT in humid climates.
- If wearing NBC clothing (MOPP 4) add **10°F** to WBGT.

Heat Category	WBGT Index, F°	Easy Work		Moderate Work		Hard Work	
		Work/ Rest	*Water Intake (Qt/H)*	*Work/ Rest*	*Water Intake (Qt/H)*	*Work/ Rest*	*Water Intake (Qt/H)*
1	78° - 81.9°	NL	½	NL	¾	40/20 min	¾
2 (GREEN)	82° - 84.9°	NL	½	50/10 min	¾	30/30 min	1
3 (YELLOW)	85° - 87.9°	NL	¾	40/20 min	¾	30/30 min	1
4 (RED)	88° - 89.9°	NL	¾	30/30 min	¾	20/40 min	1
5 (BLACK)	> 90°	50/10 min	1	20/40 min	1	10/50 min	1

Table 1.7.2-2. Fighter Index of Thermal Stress (FITS) Reference Values and Flag Colors

Dry Bulb Temperature (°F)	Zone	Dew Point Temperature (°F)								
		30	40	50	60	70	80	90	100	>110
70	NORMAL	70	73	76	81	86	X	X	X	X
75	NORMAL	74	77	80	84	89	X	X	X	X
80	NORMAL	77	80	83	87	92	98	X	X	X
85	NORMAL	81	83	86	90	95	101	X	X	X
90	NORMAL	84	87	90	93	98	104	110	X	X
95	NORMAL	88	90	93	96	101	108	112	X	X
100	CAUTION	91	93	96	99	104	109	115	122	X
105	CAUTION	94	96	99	102	107	112	118	124	X
110	CAUTION	97	99	102	105	109	114	120	126	133
115	DANGER	100	102	105	109	112	117	123	129	136
120	DANGER	104	105	108	111	115	120	125	131	138

Generally, evaporative heat loss is the most significant method for cooling of the body when the air temperature is greater than the skin temperature. If the conditions hold true and air temperature is higher than skin temperature and air humidity is less than the vaporization of water from skin to air, the evaporative cooling can account for all heat loss. Air movement, i.e., convection, is a major aid to the evaporative process as well.

1.7.2.2 Physiological Response to Heat Exposure. To maintain the narrow range of **core body temperature (T_C)**, in addition to the external environmental factors, the body will also depend upon physiological and behavioral responses for

modification. Unfortunately, behaviorally, military personnel may be able to override the common-sense factor of the physiological responses simply due to motivation of mission completion and may succumb to overexposure to heat stress. The **heat defense response** (increased sweating and vasodilation of the skin) is the process that is responsible for body heat loss via **evaporation**, **convection,** and **conduction** by altering skin blood flow. Evaporation is dependent upon sweat rate production and is reduced due to the environmental factors of high air humidity and low air movement; hot, humidified air stays close to the body and minimizes the skin's contact of cooler, less humid air.

As the T_C of the body is maintained through the heat defense response, then heat balance is reestablished and further action is not required. However, if the heat gain exceeds the heat loss and the body cannot dissipate the heat, then the heat balance moves towards heat gain and the thermal heat strain will eventually ensue. With the increase in heat strain, the normal response is to vasodilate to increase skin blood flow. If successful, the T_C will stabilize as the skin temperature begins to decrease proportional to the reduced heat strain. However, if the T_C stays elevated and skin blood flow stays high, then there's the potential the high skin blood flow might affect cardiovascular function. With increased peripheral blood flow, there's less blood centrally and that negatively affects cardiac filling and stroke volume, so heart rate must increase to maintain cardiac function. The sympathetic nervous stimulation attempts to compensate the reduced cardiac function by increasing myocardial contractility to deliver oxygenated blood to the visceral tissue; i.e., muscle and skin. If excessive, the improper redistribution in blood flow might lead to heat stress injuries.

Dehydration might cause additional heat injury due to excessive water loss, especially in nonacclimatized bodies where the **sweat rate** is a maximum of 1.5 L/hr. Dehydration can reduce evaporative and convection heat loss, an increase in T_C by 0.2ºC (0.36ºF) per every 1% body weight loss, increase in cardiac strain by approximately 5 BPM per 1% body weight, reduction in physical work capability, and reduction in T_C tolerance. Physical work capacity may be reduced in temperate environments by approximately 50% when the human body experiences 4% body weight loss. Just as one might want to avoid dehydration, it is also essential to understand that one can overconsume water (**hyperhydration)** and induce a state of low blood sodium (**hyponatremia)**.

1.7.2.3 Psychological Response to Heat Exposure. Unfortunately, the research on the effects of heat stress and mental performance is not as extensive as it is on the physiological response to heat stress. Mentally, heat stress reduces one's ability to perform cognitive functions, primarily due to the thermal discomfort accompanied with high skin temperature, high skin moisture, and increased cardiovascular strain. Mental decrements in performance occur in boring, monotonous, repetitive tasks; tasks that require attention to detail, concentration, and short-term memory and tasks that are not self-paced may degrade from heat stress. Heat stress is responsible for slowed reaction and decision times, increase in error of omission, and slowed performance times in routine tasks, with slight degradation in vigilant task performance after 30 min progressing to a marked decrement within 2 to 3 hr. A minor 2% body weight loss due to dehydration affects serial addition, response time, and word recognition during heat stress exposure and will probably be exacerbated as dehydration worsens.

1.7.2.4 Effect of Self-Imposed Factors on the Physiological Response to Heat Exposure. The consideration of individual- and mission-imposed factors and how they could negatively affect human performance under heat stress exposure are important. There is an increase in the likelihood of heat strain and/or heat casualties if one or more of the following risk factors are present close to or the day of the event: dehydration, electrolyte depletion, poor nutrition, lack of acclimatization, poor physical condition, excessive body weight, skin disorders, medications/over-the-counter medications, alcohol, illness/disease, and genetics. These heat exposure risk factors can be further divided into individual- and mission-imposed factors; **individual imposed factors** are defined as those risk factors that might negatively impact the mission and are under your complete control. For example, dehydration, electrolyte depletion, poor physical condition, excessive body weight, and alcohol are considered individual-imposed factors. Meanwhile, **mission-imposed factors** might include, but are not limited to, lack of acclimatization, poor physical condition, medications, illness/disease, or genetics.

The intent of understanding individual- and mission-imposed factors and their effect on human performance in heat stress exposeure is simply a necessity of prevention. **Prevention** is paramount in the reduction of heat-related injuries and casualties; since the mid-1980s through the mid-1990s, there has been a decrease in heat casualties of military recruits from 60 per 100,000 soldiers to 30 per 100,000 soldiers. It was determined that strategic planning before combat operations was a basic requirement in order for prevention to be effective. With the proper implementation of strategic planning as a preventive measure, one can mitigate the problems of hostile conditions, mission requirements, supply problems, and poor physical conditioning. In addition to dehydration being one of the most significant factors to guard against heat stress exposure, military and civilian personnel have gathered significant data that support that low aerobic fitness level (> 12 min in 1.5-mi fitness run) and high body mass index (> 26 kg/m^2) have a 9x greater risk of heat illness. Evidence also suggests that some are susceptible to malignant hyperthermia (e.g., an example of a mission-imposed threat in which a military member might have a genetic predisposition) and that approximately 17% of heat stroke victims were sick in the days prior to the heat stress exposure. Additionally, individual-imposed factors such as alcohol, poor physical conditioning, illness/disease, and medications/over-the-counter medications may impair the function of the heat defense response. Alcohol will cause dehydration and hypoglycemia, some drugs reduce sweating while others change blood flow distribution, and poor physical conditioning and illnesses reduce the human body's ability for proper thermoregulation. The best method of prevention combines the knowledge of how to minimize individual- and mission-imposed factors with allowing time for acclimatization.

1.7.2.5 Acclimatization to Heat Exposure. Military personnel must be fit-to-fight, meaning that not only do they need to know the environmental-, individual-, and mission-imposed factors but they must also be able to understand the operational scenarios and effective management of the details to properly education and train the troops about heat stress. Successful heat stress management begins with the implementation of procedures designed to mitigate the threats of heat stress exposure, and then intervention measures must be executed to reduce all the risk factors. A military member who is prepared to handle any hot environment and able to perform at

a high level of efficiency will be fit, healthy, hydrated, well-nourished, educated, and trained on all aspects of the current military operating environment and has allowed ample time for heat acclimatization.

An effective **heat acclimatization** program for any military personnel getting ready to either change operating locations or be deployed needs to consider frequency, intensity, and duration of heat exposures as well as a thorough heat strain decision process. Before the heat acclimatization program is implemented, the heat strain decision process needs to be in place and ready for any emergency action necessary. A simple **heat strain decision process** might have the following components: heat stress, mission requirements, uniforms and equipment, identification of high- and low-risk personnel, heat mitigation procedures, feedback, and review of the process for further modifications and improvements (Fig. 1.7.2-2). Once the heat strain decision process is in place for safety, the acclimatization program details can be organized and implemented.

Heat acclimatization is a 2-wk, progressive process that limits the intensity, frequency, and duration of heat exposure and physical activity with the focus being on unacclimatized personnel. As soon as the second day you might expect to see small changes of acclimatization, and the physiological strain of heat is reduced; however, by the end of the first and second week, the expectation is that personnel are approximately 50% and 80% physiologically adapted, respectively, for the "average soldier." The greater the physical fitness status the airmen are starting out with the faster they will acclimate, approximately 70% heat acclimation by the end of the first week. At this point, if no further heat stress exposures occurred, then effects of the acclimatization would last about 1 wk, at which point deacclimatization occurs at a rate of 75% over the next 3 wk. All military personnel will reap benefits of the heat acclimatization program; it's relative to the initial physical fitness and total heat stress exposure. The minimum heat exposure per day is 2 hr, which can be broken up into 1-hr intervals and must consist of aerobically based endurance activities (e.g., jogging or marching) that gradually progress up in workload and time. Personnel will only acclimate to the environment to which they have been exposed; if they rest in heat then that's what their relative work capacity will be once placed in the operational environment. Once deployed, continue the heat stress exposures based upon the slowest participant and keep account of the performances of the least- and most-motivated personnel – these people are potential safety hazards – always monitoring the work/rest cycles and hydration consumption (Table 1.7.2-2).

1.7.2.6 Medical Considerations. The medical needs of heat stress exposure casualties should be viewed as a continuum of signs and symptoms that can overlap one another and quite often are not clear-cut in presentation, which can lead to diagnostic issues due to lack of recognition (Fig. 1.7.2-3). The purpose of the following section is to present a simplified version of heat stress exposure injuries and illnesses to aid in the recognition. However, the aspect of treatment is minimized due to the fact that medically qualified personnel need to be the service providers when extreme conditions manifest. From a prevention perspective, it is important that all military personnel be knowledgeable about heat stress exposure, the recognition of heat stress signs and symptoms, and the basics in care and treatment of heat stress illnesses and injuries so as to provide supportive aid as necessary until medical interventions can be administered by qualified personnel.

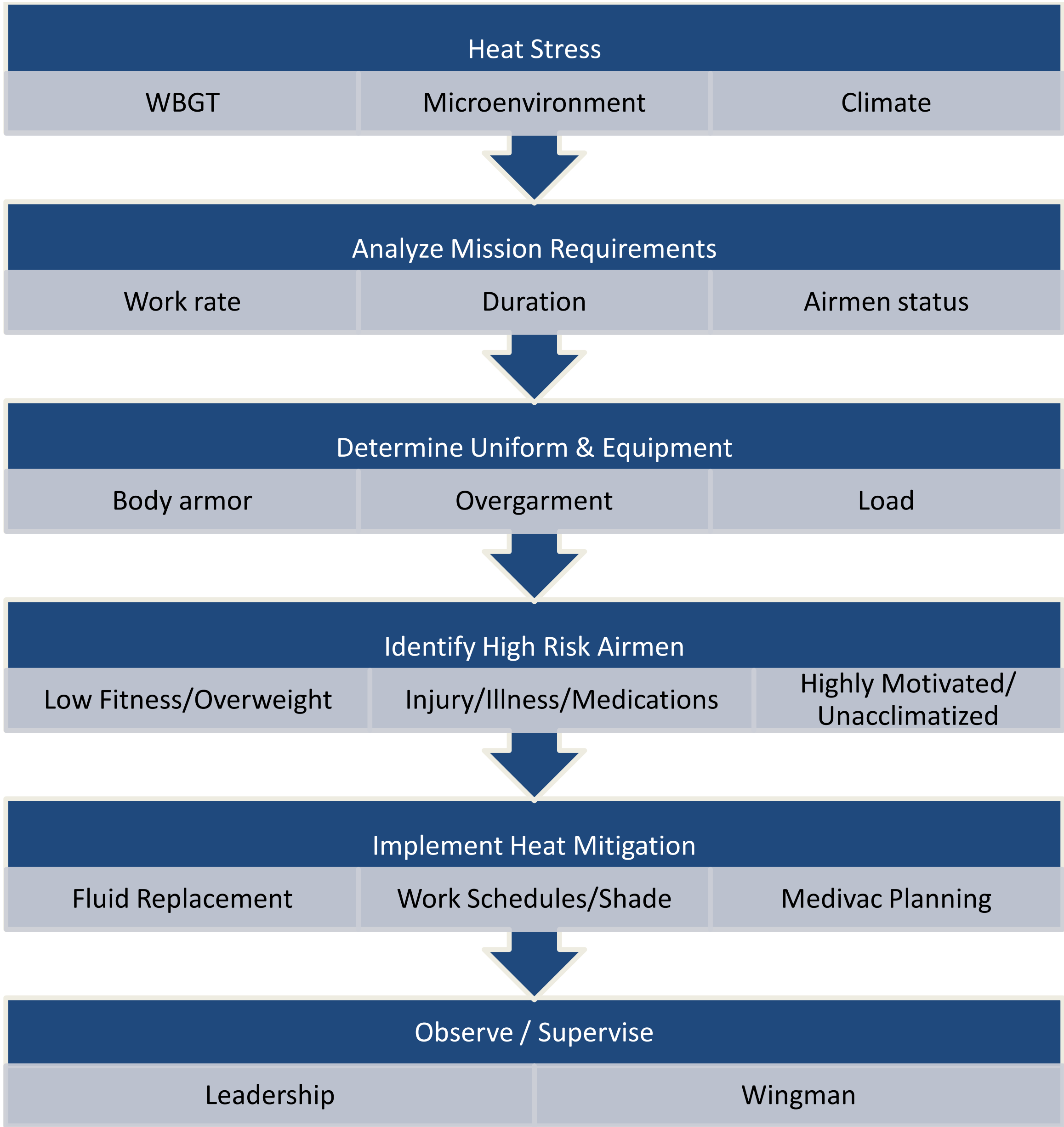

Figure 1.7.2-2. Heat Strain Decision Process

As stated previously, the classification of heat stress exposure injuries and illnesses can be a difficult task due to the fact that an individual may not always present with a standard list of signs or symptoms in a particular order over a set period of time, every single time (Fig. 1.7.2-4). Holding all things equal, generally speaking, heat stress exposure casualties will present with minor **heat illnesses** first that progress to **exertional heat injuries** and ultimately can terminate in a **heat stroke**, all of which can be caused by the imbalance between the heat gain (i.e., metabolic, physical activity, environmental) and heat loss (i.e., heat defense response), which culminates in the rise of core body temperature as a dysfunction of the body's compromised thermoregulatory response.

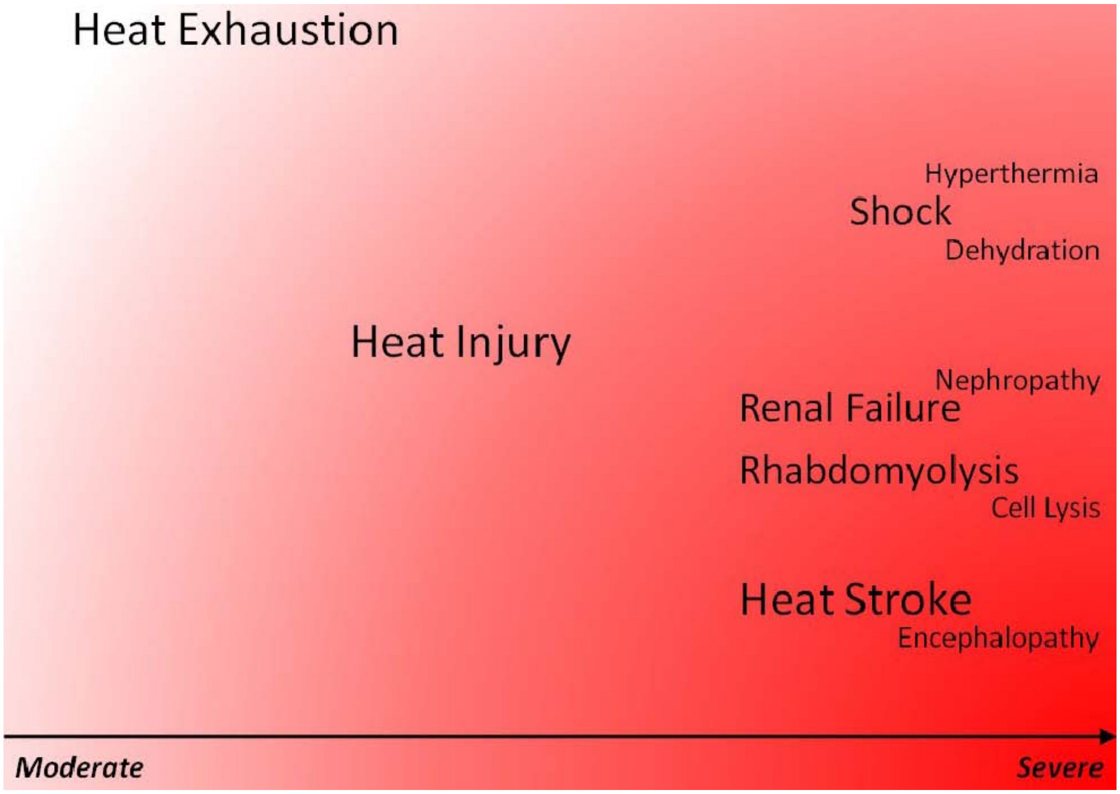

Figure 1.7.2-3. Heat Stress Exposure Spectrum

Warning Signs and Symptoms of Heat Stress and Illness

*With **any** of the below symptoms or signs, immediately call for medical evaluation by a 91W (Medic). If 91W is not immediately available, call for Medevac or ambulance.*

INDICATIONS OF POSSIBLE HEAT ILLNESS	
MORE COMMON SIGNS / SYMPTOMS • Dizziness • Headache • Dry mouth • Nausea • Unsteady walk • Weakness • Muscle cramps	**IMMEDIATE ACTIONS** • Remove from training • Allow casualty to rest in shade • Take sips of water • While doing the above, call for Medic evaluation of the soldier (Medic will monitor temperature and check for mental confusion) • If no medic is available call for ambulance or Medevac
SERIOUS SIGNS/ SYMPTOMS • Hot body, high temperature • Confusion (Do Mental Status Assessment) • Vomiting • Involuntary bowel movement • Convulsions • Weak or rapid pulse • Unresponsiveness, coma	**Immediately call Medevac or ambulance for emergent transport while doing the following:** • Lay person down in shade with feet elevated until Medevac or ambulance arrives • Undress as much as possible • Pour cool water over person and fan • Give **sips** of water while awaiting ambulance (if conscious) • Monitor airway and breathing until ambulance or Medevac arrive

MENTAL STATUS ASSESSMENT

A sign that the soldier is in a serious life-threatening condition is the presence of mental confusion (with or without increased temperature). Anyone can do a mental status assessment asking some simple questions:

Call for emergency Medevac or ambulance if any of the following exist:

What is your name?
(Does not know their name.)

What month is it? What year is it?
(Does not know the month or year.)

Where are we/you?
(Does not know the place where they are at.)

What were you doing before you became ill?
(Does not know the events that led to the present situation.)

Figure 1.7.2-4. Heat Stress Illness Signs and Symptoms

On the left end of the heat stress continuum (Fig. 1.7.2-3), with moderate severity, the minor heat-related illnesses are **heat edema**, **miliaria rubra**, **sunburn**, **heat tetany**, **heat syncope**, and **heat cramps**. **Heat edema** is commonly known for swelling in the periphery of the hands and feet that usually manifests in tight-fit clothing on those areas. The cause of heat edema is unknown, so treatment is equally vague, with the focus on comforting the individual and evaluating the area as needed; time for acclimatization will usually resolve the problem. **Miliaria rubra**, also known as "prickly heat" or "heat rash," is a condition of the skin occurring when eccrine secretory sweat glands become clogged, which can lead to redness and inflammation of the affected area. Treatment consists of conditions that keep the affected area cool and dry and the proper application of prescribed medication; good hygiene and loose clothing aid in the healing process. The primary concern should focus on the fact that the affected area cannot assist in thermoregulation; therefore, the person's thermoregulatory system is compromised proportionally to the size and severity of the area. One must pay close attention to those with heat rash as to not exacerbate the condition by poor implementation of prevention measures. **Heat tetany**, i.e., long tonic spasm of muscle, is caused by simple hyperventilation in unacclimatized personnel and should be treated appropriately. The condition will include tightening of muscles with potential numbness and tingling; simply calm and control breathing to mimic a normal rate and depth of breath. **Heat cramps** should not be confused with heat tetany. Heat cramps are short, recurring muscle contractions lasting 2 to 3 min that may present in the form of a palpable ball after vigorous activity. The condition is thought to rise from sodium depletion with the resultant effect of a calcium increase in the intracellular muscle tissue, thus causing the cramps; muscle cramps usually subside upon electrolyte replenishment. The final minor heat-related illness is syncope. **Heat syncope** or "parade syncope" can range from lightheadedness to loss of consciousness due to peripheral blood pooling and a reduction in cardiovascular ejection fraction. The reason for the vasodilation and reduced venous return is focused on the heat stress exposure and the defense response; compounding variables that would exacerbate the condition include vigorous activity and weather conditions. Heat syncope presenting after more than 5 days of acclimatization might indicate other medical conditions such as heat exhaustion or exertional heat injury.

Heat exhaustion is the most common type of heat-related injury and falls under the leftmost aspect of the heat stress exposure continuum as moderate in severity. There is no organ damage from heat exhaustion, and personnel succumbing to the heat stress exposure with these signs and symptoms will normally recover quickly. The occurrence of heat exhaustion is preceded by a demand mismatch of blood flow between skin that is involved in the heat defense response and delivery to active muscle mass and organs. The cardiac output of the heart is unable to provide sufficient ejection fraction per beat to deliver oxygen-rich blood to all demanding tissues, thus exhaustion due to heat stress. The signs and symptoms personnel may experience might range from generalized weakness, fatigue, ataxia, dizziness, headaches, nausea, vomiting, malaise, hypotension, tachycardia, muscle cramps, hyperventilation, to transient changes in mental alertness. The onset and/or severity of these signs and symptoms can be exacerbated by dehydration, hypovolemia, peripheral blood pooling, and potentially failure of splanchnic vasoconstriction. With heat exhaustion, the individual is combating excessive cardiovascular demand and some level of electrolyte depletion but is still able to thermoregulate through sweating, and it may be more profuse than normal. Recovery from an episode consists of removal of the personnel

from the hot environment, replenishment of electrolytes, plus rest. If the casualty is young and fit, then field treatment is sufficient; however, if the condition continues to deteriorate, then medical intervention is required. The same holds true for recurrent episodes, which may indicate reduced heat tolerance.

As the intermediate level of severity on the heat injury continuum, **exertional heat injury** and **rhabdomyolysis** can be difficult to distinguish from heat exhaustion unless vital signs and blood chemistries are being monitored. Heat injury and rhabdomyolysis show evidence of organ (i.e., kidney or liver) and tissue (i.e., muscle) damage or dysfunction but do not include neurological aspects as seen with heat stroke. Personnel will still be sweating, possibly profusely, thus the heat defense response is still functioning and cooling can occur; however, precautionary measures dictate immediate active cooling to reduce core body temperature below 38.3ºC (101ºF) and rehydration plus electrolytes. Exertional rhabdomyolysis may not have an increase in T_C, but blood chemistries will reveal higher levels than normal in creatine kinase, phosphate, potassium, uric acid, and myoglobin, as they have been released from the muscle tissue due to cellular destruction. Medical intervention is necessary in these intermediate-level heat injuries with the application of rest in a cool environment and fluid-electrolyte replacement.

Heat stroke is the failure of the thermoregulatory system and must be handled as a catastrophic medical emergency. In heat stroke, the T_C has elevated above 40°C (104°F), causing central nervous system dysfunction and organ system failure. The central nervous system disorders consist of an ambiguous set of signs or symptoms that may be transient or persistent, with the resultant dysfunction of delirium, convulsions, or coma. The heat stroke casualty might exhibit onset signs and symptoms of headaches, dizziness, drowsiness, restlessness, ataxia, confusion, and irrational or aggressive mental status. There are two categories of heat stroke, **classical** and **exertional**, presenting with dissimilar signs and symptoms because of the environmental settings and the affected personnel; Table 1.7.2-3 outlines the differences. The classical signs and symptoms of classical heat stroke (e.g., coma, convulsions, and cessation of sweating) may be late or delayed in exertional heat stroke, while rhabdomyolysis and renal failure will be present for exertional heat stroke. These diagnostic criteria can be misinterpreted because of a strict adherence, which often leads to an under- or misdiagnosis of exertional heat stroke.

The principal effect of heat stroke injury focuses on the damage to organ tissues, such as brain, liver, kidney, and muscle, which interrupts homeostasis. Compounding factors that contribute to the increased severity of the condition are mostly due to the magnitude of T_C, the duration of exposure, and any other additional underlying physiological conditions, for example, tissue ischemia, hypokalemia, exercise-induced lactic acidosis, and any systemic inflammatory responses. Cognitively, a heat stroke victim's dysfunction may include delirium, euphoria, coma, hallucinations, rapid eye movement, and seizures; seizures might alternate with tonic contractions, tremors, and muscle cramps. Hepatic liver injury is generally seen in heat stroke conditions and can lead to hypoglycemia and jaundice 24 to 36 hr post-onset. Acute renal failure occurs in approximately 30% of exertional heat stroke cases and is preceded by rhabdomyolysis. The muscular system is often affected by the increase in plasma levels of myoglobinuria and muscle enzyme due to the presence of rhabdomyolysis accompanied by muscle rigidity. Coagulatory issues, e.g., microthrombi, arise in the blood due to rhabdomyolysis, hepatocyte, and vascular endothelium damage as well as thermal platelet activation. Additionally, cardiac (i.e., hyper- or hypodynamic circulatory

states) and gastrointestinal tract (i.e., diarrhea or vomiting) dysfunction or pulmonary edema may be present if the severity of the injury is extreme. The outcome of the heat stroke casualty is dependent upon the duration and magnitude of the elevated T_C temperature, and the most important therapeutic measure is the rapid cooling of the body. Any means should be taken to rapidly cool the body, from immersion in cold water, to ice baths, to the use of ice packs; rapid cooling can reduce the mortality rate of heat stroke casualties from 50% to 5%. During mission planning and execution, the obstacle that often needs to be overcome regarding heat stress illness and injury is the possible perception that it is only a minor threat. The responsibility lies with all military personnel, directly and indirectly, to identify, assess, analyze, decide, implement, and review; prevention is the key factor.

Table 1.7.2-3. Heat Stroke Categorical Differences

Personnel Characteristics	Exertional	Classical
Age	15-45 years of age	Child or elderly
Health	Usually healthy	Chronic illness common
History of illness	Common	Unusual
Environment	Variable	Prolonged heat
Activity	Strenuous exercise	Sedentary
Drug use	Usually none, some use of ergogenic aids or stimulants	Diuretics, antidepressants, anticholinergics, phenothiazines
Sweating	Present	Usually absent
Acid-base disturbances	Lactic acidosis	Respiratory alkalosis
Acute renal failure	Common (≈30%)	Rare (<5%)
Rhabdomyolysis	Common	Seldom severe
Hyperuricemia	Marked	Modest
Creatinine ratio (blood)	Elevated	1:10
Creatine-kinase, aldolase	Markedly elevated	Mild elevation
Hyperkalemia	Often present	Usually absent
Hypercalcemia	Common	Uncommon
Disseminating Intravascular Coagulation	Maybe marked	Mild
Hypoglycemia	Common	Uncommon

1.7.2.7 Prevention. To successfully prevent a heat stress emergency, military personnel must be knowledgeable in the information, proficient in the application of procedures through education and training, and, ultimately, consistent in implementation of mission planning. Aspects of planning to consider are the environmental settings in which personnel will be exposed, the knowledge of how that will affect their performance, when to implement procedures to mitigate the threat of a heat stress casualty, and the efficient execution of emergency procedures when required. From a prevention perspective, military personnel must consider the things they have within their control to reduce their risk of succumbing to heat stress injury: fluid/electrolyte replacement, nutrition, and personal clothing ensembles.

First and foremost are the fluid and nutrition requirements for military personnel when they're placed in an environment that exposes them to heat stress. **Hydration** and **nutrition** considerations for military personnel exposed to hot environments must be based on the simple premise that they will sweat and feel apathy towards food. With an increase in heat stress, there is a concomitant increase in **sweat rate** and, therefore, body water loss. Thirst is not a sufficient sign of hydration requirements because most often personnel have lost about 2% of body weight from water loss; they are already dehydrated once thirst is stimulated. Under normal conditions, water

replacement is not a primary concern, as rehydration occurs during mealtime. However, satiety for food is suppressed during heat stress, and thus the desire to drink might be suppressed simply because meals are eliminated, thus reducing water intake indirectly. Common methods to reensure water intake is sufficient consist of the frequency, volume, and clarity check method or the weight-loss method. Albeit a little unscientific, operationally the urine check method is easy to employ. Generally, a good sense of hydration is exemplified in frequent, large-volume, and clear urination; conversely, infrequent, small-volume, and dark-colored urine is an indication of dehydration. The weight method is based upon Archimedes' principle and simply stated is as follows: 1 kg of body weight loss during a bout of physical activity under hot stress exposure is equal to 1 L of water loss; remember to subtract out the weight of the unsoaked and soaked clothing. Truly, the most effective method for consistent hydration status is to allocate work/rest cycles, water breaks, and mealtimes. The fluid supplied during the breaks should be cool (50°F to 60°F) for optimal palatability and contain water, electrolytes, and a carbohydrate replacement. Sweat rates can range considerably, as they relate to the physical activity level and the environment. Sweat rates for the most common military function can be 0.3 to 1.0 L/hr, with rates up to 2.2 L/hr while donning NBC protective clothing while working. Based upon Figure 1.7.2-5 and Table 1.7.2-4, these normative data provide caloric expenditures per job duty based upon the current environmental temperature and correlate that to a specific water requirement.

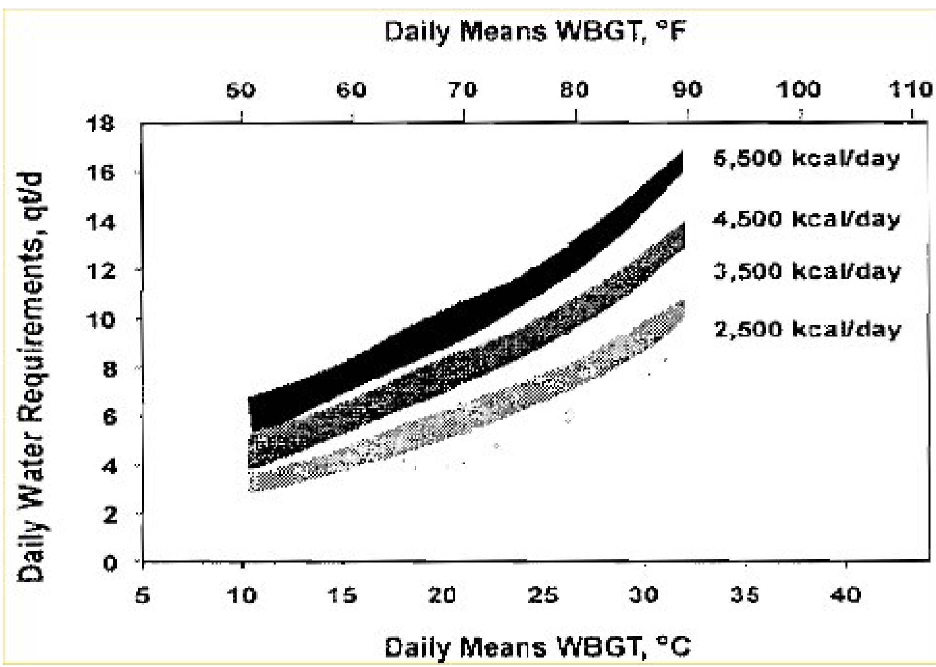

Figure 1.7.2-5. Nomogram for Daily Water and Nutritional Consumption

Table 1.7.2-4. Military Personnel Total Daily Caloric Expenditure per Job Duty

Group	Activity	kcal/day
Army Special Forces	Combat exercise, temperate	3,400
Army Engineers	Build road and airstrip @ altitude	3,549
Army Transportation Company	Garrison	3,568
Marine Combat Engineers	Construction	3,668
Israeli Infantry	Combat exercise, summer	3,937
Army	Support hospital	3,960
Army Ranger	Training course	4,010
Army Ranger	Training course	4,090
Marine	Artillery exercise, desert	4,115
Marine	Combat exercise, winter	4,198
Army	Artillery exercise, winter	4,253
Israeli Infantry	Combat exercise, winter	4,281
Army Special Forces	Combat exercise, winter	4,558
Marine	Crucible, women	4,679
Australian Infantry	Jungle training	4,750
Army Special Forces	Assessment school	5,183
Army Ranger	Combat exercise	5,185
Norwegian Ranger	Training course	6,250
Marine	Crucible, men	6,067
Average		**4,405**

Electrolyte replacement can take place in many different forms; most often under normal conditions, the normal meals throughout the day are adequate enough to replenish the daily turnover of electrolytes. However, the additional aspect of sweating from heat stress exposure increases sodium loss, ≈10 to 70 mmol/L, but that can be reduced by 50% through heat acclimatization. Most military personnel living and working in a hot environment, on average, lose approximately 4 to 9 g of sodium per day. If deployed, the consumption of three Meals, Ready to Eat (MREs) will adequately replace the sodium loss, but all the meal must be eaten including the salt packets as well. Similar to the water requirement nomogram, Figure 1.7.2-6 depicts the sodium requirement per day based upon the ambient temperature under specific caloric requirements. Use Table1.7.2-5 to establish caloric requirements per job duty.

From a thermal protection viewpoint, clothing can be either a major advantage or disadvantage, depending upon the individual- and mission-imposed stresses. The concept of multi-layers is essential in a hot environment. Long-sleeved shirts provide protection from radiant heat and skin protection from heat injuries such as sunburns and allow military personnel to take protective layers off as needed to provide a balance between radiant stress and thermal stress. The full spectrum begins with mission planning, when variables such as clothing layers required (e.g., cotton underwear, fire-retardant coveralls, G-suit, parachute harness, gloves, boots, etc.), environmental conditions (i.e., on earth, in the cockpit, in the back of the aircraft with the ramp deployed, at altitude, over the water, etc.), and nutritional and hydration status (e.g., pre-flight, during flight and post-flight) are considered. Mission planning is essential for the prevention of heat stress injuries/illnesses and must take into account individual- and mission-imposed stresses.

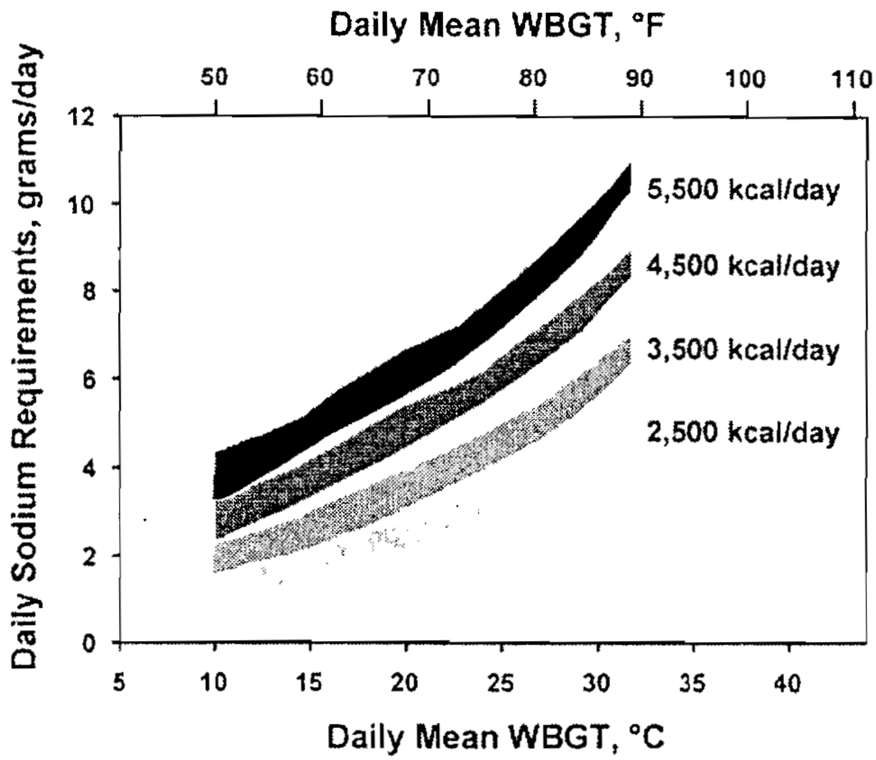

Figure 1.7.2-6. Nomogram for Daily Sodium and Nutritional Consumption

Ultimately, the responsibility of training and its proper implementation lie with the unit leadership. The United States Army Center of Health Promotion and Preventive Medicine has distributed a heat risk manual that outlines a five-step **risk management** tool to prevent heat stress causalities (Fig. 1.7.2-7). The first step is to identify the hazards, such as weather conditions; inventory of required supplies; and self-imposed factors. The second step of hazard assessment focuses on the proper use of heat index charts relating to environmental conditions, work intensity, food and clothing, and injuries stratified into risk categories. The development of control points establishes limits for the third step. The implementation, supervision, and evaluation of the risk management plan are the final steps of the process, steps four and five. The heat stress exposure risk management tool is only effective if it remains as a dynamic loop that continues to take into account the ever-changing variables of the ambient environment, military personnel, and operational mission. Situational awareness is paramount when military personnel perform active and nonactive duties in hot environments, and if the proper preventive measures are implemented, heat stress exposure injuries such as hyperthermia, heat exhaustion, heat injuries, and heat stroke can be prevented. Prevention begins in pretraining preparation, use of heat stress index tables chart to manage personnel time of exposure to the hot environment, risk assessment by medical personnel on active duty personnel, an established buddy-system to advise one another in early detection of hazardous factors, and, importantly, leadership: leading by example.

Risk Management is the process of identifying and controlling hazards to protect the force.

Possible Outcomes of inadequate climatic heat management:

Casualty	Risk Severity
Heat Cramps	Marginal
Heat Exhaustion	Critical
Heat Stroke	Critical-Catastrophic
Water Intoxication (Over Hydration)	Critical-Catastrophic

The Five Steps of Risk Management are:

1 Identify Hazards

High heat category, especially on several sequential days
(Measure WBGT when ambient temperature is over 75° F)

Exertional level of training, especially on several sequential days

Acclimatization (and other individual risk factors – see table below)

Time (length of heat exposure and recovery time)

Individual Risks for Heat Casualties (The more factors, the higher the risk)

- **Not acclimatized** to heat (need 10-14 days to get trainees adequately acclimated)
- Exposure to cumulative days (2-3 days) of any of the following
  - Increased heat exposure
  - Increased exertional levels.
  - Lack of quality sleep
- Poor fitness (Unable to run 2 miles in < 16 minutes)
- Overweight
- Minor illness (cold symptoms, sore throat, low grade fever, nausea, vomiting)
- Taking medications (either prescribed or over the counter)/ supplements/ dietary aids Ex: Allergy or cold remedies. Ephedra supplement
- Use of Alcohol in the last 24 hours
- Prior history of heat illness (any heat stroke, or >2 episodes of heat exhaustion)
- Skin disorders such as heat rash and sun burn which prevent effective sweating
- Age > 40 years

Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties

2 Assess Hazards

- When ambient temperature is over 75° F, constantly assess the **heat category** using Wet Bulb Globe Temperature (WBGT)
- Know your soldiers! Identify early who will be at increased risk based on **individual risk factors**.
- Check **hydration status** at the end of each training day. Give extra fluid at night and in the morning if hydration is inadequate.
  - Review Riley (water) card or Ogden cords
  - Ask about urine color. Urine is clear if well hydrated
- Daily **assess the overall risk** for developing a heat casualty (may use a risk matrix).

The following matrix has been used successfully through experience by Commanders.

Example of a Heat Injury Risk Management Matrix

Scores assigned to different conditions based on risk for developing a heat injury.
This scoring system: 0= Low risk; 1=Medium risk, 2=High risk; 3=Extreme risk

RISK FACTORS	Level of Risk (For each Factor Circle the Appropriate Condition)			
	0	1	2	3
Risk Management Worksheet	All control measures implemented			Not all control measures implemented
Heat (WBGT at site)	None (Less than Category 1)	Category 1	Category 2 and 3	Category 4 and 5
No. Sequential Days Heat Cat 5	0	1	2-3	$\geq$4
Heat Injuries in the unit in Past 2 Days	None	Heat Cramps	Heat Exhaustion	Heat Stroke*
Work in Past Two Days (see below)	Easy	Easy	Moderate	Hard
Projected Work for the Present Day	Easy	Easy	Moderate	Hard
Heat Acclimatization Days	>13	7-13	3-6	<3
Leader/Cadre Presence	Full time	Substantial	Minimal	None
Length of Duty Time of Cadre	18 Months	7-18 Months	1-6 Month	< 1 Month
Communication System	Radio and Phone	Phone Only	Radio Only	None
Rest in Previous 24 Hours	> 7 Hours	5-7 Hours	2-4 Hours	< 2 Hours

Cumulative score: 25-33 = extreme risk, 16-24 = high risk, 7-15 = medium risk, 0-6 = low risk.
* If Heat Stroke has occurred in unit in past 2 days, risk level= extreme risk

Easy Work	Moderate Work	Hard Work
• Weapon Maintenance • Walking Hard Surface at 2.5 mph, < 30 lb Load • Marksmanship Training • Drill and Ceremony	• Walking Loose Sand at 2.5 mph, no Load • Walking Hard Surface at 3.5 mph, < 40lb Load • Calisthenics • Patrolling • Individual Movement Techniques. i.e. low crawl, high crawl	• Walking Hard Surface at 3.5 mph, ≥ 40 lb Load • Walking Loose Sand at 2.5 mph with Load • Field Assaults

Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties (continued)

Develop Controls

Education

- Establish SOPs. Ensure all personnel are trained and follow SOPs for Heat Casualty Prevention.
- Ensure all bulletin boards have Heat Casualty Prevention posters and all leaders have Heat Casualty Prevention aids.

Planning

- Adjust the training schedule to minimize consecutive days of heavy physical training, especially if other heat stressors exist (e.g. heat exposure and lack of quality sleep)
- Plan communications, medical and evacuation support.
- Plan and provide adequate hydration for *all* personnel (including Cadre and Drill Instructors).
- When planning training events, keep in mind:
    1. Time of day the training is conducted – morning is cooler
    2. Location of training
        - Sun vs. shade. Rest in shade.
        - Open vs. protection from wind - wind has cooling effect
        - Open up the formation to decrease heat strain.
    3. Clothing
        - Heavy, restrictive vs. loose, lightweight
    4. Where in training cycle
        - Most Heat Casualties occur in the 2nd or 3rd week of Recruit training.
        - Acclimatization can take 7-14 days, depending on the physical condition of the trainee.
- After moderate to hard work in heat category $\geq$3; take cold, nude showers at the end of the day.

Identification

- Identify previous heat exhaustion or heat stroke soldiers and mark visibly on uniform (tape or cord).
- Identify overweight soldiers and soldiers who are unfit.
- Identify soldiers on medications and mark visibly on uniform (tape or cord).
- Seriously consider taking soldiers out of training who have had alcohol within the last 24h. Seriously consider having ill soldiers seen on sick call.
- Note and document heat category hourly. Position WBGT at site of training.

Develop a Hydration Monitoring System

- Examples of monitoring methods:
    - Riley (water) card. On the card, Battle buddy is to write the amount of water the soldier has drunk.
    - Ogden Cord is 550 cord, parachute cord or shoestring that is tied to a uniform buttonhole or ear protection case. Soldiers tie a knot in the cord each time they finish a canteen (1 quart) of water.

Water Consumption Card

Name:

Time	Mon	Tue	Wed	Thur	Fri	Sat	Sun
0500-0600							
0600-0700							
0700-0800							
0900-1000							
1000-1100							
1100-1200							
1200-1300							
1300-1400							
1400-1500							
1500-1600							
1600-1700							
1700-1800							
1800-1900							
1900-2000							
2000-2100							
2100-2200							

Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties (continued)

3 Develop Controls continued

Know Standardized Guidelines for Warm Weather Training Conditions

Fluid Replacement and Work/Rest Guide

Acclimatized (after approx two weeks training) Wearing BDU, Hot Weather

		Easy Work		Moderate Work		Hard Work	
Heat Category	WBGT Index, (F°)	Work/ Rest	Water Intake (Qt/h)	Work/ Rest	Water Intake (Qt/h)	Work/ Rest	Water Intake (Qt/h)
1	78-81.9	NL	½	NL	¾	40/20 min	¾
2 (Green)	82-84.9	NL	½	50/10 min	¾	30/30 min	1
3 (Yellow)	85-87.9	NL	¾	40/20 min	¾	30/30 min	1
4 (Red)	88-89.9	NL	¾	30/30 min	¾	20/40 min	1
5 (Black)	> 90	50/10 min	1	20/40 min	1	10/50 min	1

- The work-rest times and fluid replacement volumes will sustain performance and hydration for at least 4 h of work in the specified heat category. Fluid needs can vary based on individual differences (± ¼ qt/h) and exposure to full sun or full shade (±¼ qt/h).
- NL= no limit to work time per hour.
- Rest means minimal physical activity (sitting or standing), accomplished in shade if possible.
- **CAUTION:** Hourly fluid intake should not exceed 1½ quarts.
- Daily fluid intake **should not exceed 12 quarts.**
- If wearing body armor add **5°F** to WBGT in humid climates
- If wearing NBC clothing (mission-oriented protective posture (MOPP 4)), add **10°F** to WBGT index for easy work, and **20°F** to WBGT index for moderate and hard work.

Easy Work = Walking hard surface 2.5 mph <30# load, Weapon maintenance, Marksmanship training
Moderate Work = Patrolling, Walking sand 2.5 mph no load, Calisthenics
Hard Work = Walking sand 2.5 mph w/load, Field assaults

Continuous Work Duration and Fluid Replacement Guide

Acclimatized (after approx two weeks training) Wearing BDU, Hot Weather

It is assumed the trainees performing these continuous effort tasks have not yet had heat stress or dehydration prior to this activity and will have several hours of rest afterwards.

		Easy Work		Moderate Work		Hard Work	
Heat Category	WBGT Index, (F°)	Work (min)	Water Intake (Qt/h)	Work (min)	Water Intake (Qt/h)	Work (min)	Water Intake (Qt/h)
1	78-81.9	NL	½	NL	¾	70	1
2 (Green)	82-84.9	NL	½	150	1	65	1 ¼
3 (Yellow)	85-87.9	NL	¾	100	1	55	1 ¼
4 (Red)	88-89.9	NL	¾	80	1 ¼	50	1 ¼
5 (Black)	> 90	180	1	70	1 ½	45	1 ½

- NL can sustain work for at least 4 hours in the specified heat category.
- Fluid needs can vary based on individual differences (± ¼ qt/hr) and exposure to full sun or full shade (± ¼ qt/hr).

Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties (continued)

4 Implement Controls

Decision to accept risk is made at the appropriate level

- Made in accordance with appropriate MACOM regulation

Identified controls are in place

- Update WBGT hourly when ambient temperature is ≥ 75°F.
- Adhere to work/rest cycle in high heat categories. Rest in shade.
- For tasks requiring continuous effort, adhere to guideline and allow extended rest afterwards.
- Training event incorporates good prior planning.

Monitor and enforce hydration standard

- Encourage frequent drinking, but not to exceed **1 ½** quarts per hour or **12** quarts per day. Make water more palatable, if possible, by cooling.
- Do not allow soldiers or trainees to empty canteens to lighten load (consider imposing a penalty in timed events).
- Ensure soldiers are well hydrated before training. Ask about urine; urine is clear if well hydrated.
- Check Riley (water) card or Ogden Cord frequently.

Monitor and enforce eating meals

- Ensure all meals are eaten during the meal break
- Ensure adequate time to eat and drink meals
- Table salt may be added to food when the heat category is high. Salt tablets are *not* recommended

Execute random checks

- Spot checks by Cadre, Senior NCO's, and Drill Instructors
- Enforce battle buddy checks – need to be aware of each other's eating, drinking and frequency of urination
- Plan placement of leaders to observe and react to heat injuries in dispersed training

Follow clothing recommendations

- Heat category 1-2: no restrictions
- Heat category 3: Unblouse trouser legs, unbuckle web belt
- Heat category 4-5:
  - Unblouse trouser legs, unbuckle web belt
  - Remove t-shirt from under BDU top or remove BDU top down to T-shirt (depends whether biting insects are present)
  - Remove helmets unless there are specific safety reasons to keep them on (e.g.: range).
- MOPP 4: Add **10°F** to WBGT index for easy work, and **20°F** to WBGT index for moderate to hard work.

Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties (continued)

5 Supervise & Evaluate

- Enforce SOPs
- Delegate authority to ensure control measures have been implemented
- Monitor adequacy/progress of implementation of control measures
- Conduct spot checks of cadre. Do cadre have current WBGT? Are cadre implementing work/rest/drink cycles? Make on-the-spot corrections. Lead by example.
- Conduct spot checks of recruits. Ask recruits questions while observing their mental status and physical capabilities. Look out for common signs and symptoms which can rapidly progress to serious signs and symptoms. Ask recruits when did they last urinate and was their urine clear?
- If 1-2 recruits become heat casualties, stop all training and evaluate each soldier for early signs and symptoms of becoming an impending heat casualty.
- When controls fail, heat injuries occur. The ability to recognize heat injury is paramount. Take immediate action if any heat injuries are observed or suspected. Stop-rest-cool then evaluate in accordance with warning signs and symptoms. If in doubt, evacuate.

Warning Signs and Symptoms of Heat Casualty and Water Intoxication

Indications of possible Heat Casualty	
More Common Signs / Symptoms • Dizziness • Headache • Nausea • Unsteady walk • Weakness or fatigue • Muscle cramps	**Immediate Actions** • Remove from training • Allow casualty to rest in shade • Loosen clothing • Take sips of water • While doing the above, call for a Medic to evaluate the soldier (Medic will monitor temperature and check for mental confusion) **If no medic is available call for ambulance or Medevac**
Serious Signs / Symptoms • Hot body, high temperature • Confusion, agitation (Mental Status Assessment) • Vomiting • Involuntary bowel movement • Convulsions • Weak or rapid pulse • Unresponsiveness, coma	**Immediately call Medevac or ambulance for emergency transport while doing the following:** • Lay person down in shade with feet elevated until Medevac or ambulance arrives • Undress as much as possible • Aggressively apply ice packs or ice sheets • Pour cold water over casualty and fan. • Give *sips* of water while awaiting ambulance (if conscious) • Monitor airway and breathing until ambulance or Medevac arrive

Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties (continued)

5 Supervise & Evaluate continued

Indications of possible Water Intoxication (Over Hydration)

Signs and Symptoms	What to do:
Confusion Weakness Nausea Vomiting	**Ask these questions to the soldier or battle buddy:** 1. Has soldier been eating? Check rucksack for # of MRE's left. 2. Has soldier been drinking a lot? (suspect water intoxication if soldier has been drinking constantly). 3. How often has soldier urinated? (frequent urination seen with water intoxication; infrequent urination with heat illness) 4. What color is urine (clear urine may indicate over hydration) If soldier has been eating, drinking and urinating a lot, yet has these symptoms, **immediately call Medevac or ambulance for emergency transport**

Mental Status Assessment

An important sign that the soldier is in a serious life-threatening condition is the presence of mental confusion (with or without increased temperature). Anyone can do a mental status assessment asking some simple questions.

Call for emergency Medevac or ambulance if *any* of the following exist:

What is your name?
(Does not know their name.)

What month is it? What year is it?
(Does not know the month or year.)

Where are we/you?
(Is not aware of location or surroundings.)

What were you doing before you became ill?
(Does not know the events that led to the present situation.)

See http://chppm-www.apgea.army.mil/heat for electronic versions of this document and other heat injury prevention resources

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Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties (continued)

Hot Weather Casualties and Injuries Chart

- Train commanders and soldiers on heat injury prevention and heat risk assessment
- Remember the acronym H-E-A-T when training in hot weather
  (H: heat category; E: exertion level; A: acclimatization; T: time of heat exposure and recovery time)
- Follow recommended fluid replacement guidelines and ensure nutritional requirements are met

Hot Weather Injuries and Casualties

Cause	Symptoms	First-Aid	Prevention
Sunburn			
• Exposure of skin to direct sun • Can occur on overcast days	• Red, hot skin • May blister • Moderate to severe pain • Can result in fever	• Move to shade; loosen clothing if necessary • Apply cold compress or immerse in cool water • Apply moisturizing lotion to affected areas • Hydrate with fluids • Administer analgesics for pain or fever • Do not break blisters	• Adequate sun protection • Use sunscreen liberally and apply often, especially when sweating excessively • Select SPF 15 or higher • Proper wear of clothing, cap
Heat Rash (Prickly Heat)			
• Restrictive clothing • Excessive sweating • Inadequate hygiene • Causes heat intolerance if 20% of skin affected	• Red, itchy skin • Bumpy skin due to blocked pores • Moderate to severe itching • Can result in infection	• Apply cold compress or immerse in cool water • Keep area affected dry • Control itching and infection with prescribed medications	• Proper wear of clothing • Shower (nude) after excessive sweating
Heat Cramps			
• Excessive loss of salt from body due to excessive sweating • Not acclimatized to hot weather	• Painful skeletal muscle cramps or spasms • Mostly affects legs and arms	• Replace salts • Sit quietly in the shade or cool area • Massage affected muscle • Drink oral rehydration package or sports drink • Drink 0.05 to 0.1% salt solution (add ¼ of MRE salt packet to 1 quart canteen) • Get medical evaluation if cramps persist	• Eat all meals to replace salt • Consume salt-supplemented beverages if adequate meals have not been consumed prior to prolonged periods of heavy sweating • Ensure adequate heat acclimatization
Heat Exhaustion			
• Body fatigue and strain on heart due to overwhelming heat stress • Dehydration (see below) • Inadequate acclimatization • Inadequate physical fitness for the work task • Most common exertional heat illness	• Dizziness • Headache, nausea • Unsteady walk • Weakness • Fatigue • Rapid pulse • Shortness of breath	• Initiate active cooling by best means available. • Move to shade and loosen clothing • Lay flat and elevate feet • Spray/pour water on soldier and fan for cooling effect or use ice sheets around neck, arm pits and groin, if available • Monitor with the same (one) instructor or supervisor • Assess soldier's mental status every few minutes • Have soldier slowly drink one full canteen (quart) of cool water every 30 minutes with a maximum of 2 canteens • If not improved in 30 to 60 minutes, evacuate for further medical care • NOTE: Those who recover within 60 minutes should return to light duty on a profile for the remainder of the day	• Allow for acclimatization • Monitor WBGT and observe work-rest cycles • Keep soldiers in shade whenever possible • Follow water replacement guides • Identify high risk individuals • Maintain buddy system • Eat all meals in garrison and field • Do not take dietary supplements • Modify uniform accordingly • Teach early recognition of symptoms • Recognize cumulative effect of sequential hot days • Reevaluate training if several heat injuries occur
Heat Stroke			
• Prolonged exposure to high temperatures • Cumulative heat stress due to repetitive activity in hot environment • Failure of body's cooling mechanisms • Prolonged and overwhelming heat stress • Predisposing factors such as sickness, poor health or certain medications	• Any of above symptoms, but more severe • Elevated temperature, usually above 104° F • Altered mental status with confusion, agitation, delirium, disorientation • Nausea, vomiting • Can progress to loss of consciousness, coma, and seizures	• This is a **medical emergency** and can lead to death! **Evacuate** soldier to a medical facility immediately! • **Begin cooling aggressively**. Body temperature that does not go below 100° F with active cooling or ANY mental status changes calls for immediate evacuation. • Initiate measures for heat exhaustion • Apply ice packs or iced sheets • Assess soldier's mental status every few minutes • If conscious, give sips of cool water while waiting for evacuation or ambulance • Do not give water to unconscious soldier • If possible, measure body temperature • Monitor airway and breathing • If medic or CLS is present, start intravenous (IV) fluids but limit to 500 ml NS • Continue cooling during transport (until body temperature reaches 100° F)	• Follow measures for heat exhaustion • Plan medical support for heat intensive operations • Ensure appropriate Evacuation capabilities available • Ensure Preventive Medicine personnel and measures are in place
Additional Medical Considerations in the Hot Weather Environment:			
Dehydration			
• Depletion of body fluids and possibly salt	• Dizziness • Weakness and fatigue • Rapid pulse	• Replace lost water and salt • Water should be sipped, not gulped • Get medical treatment	• Drink 3-6 quarts of fluid per day • Follow fluid replacement guidelines • Consume full meals and drink at mealtime • Do not take dietary supplements
Over Hydration (Hyponatremia)			
• Over hydration or water intoxication • Decreased meals or dieting • Loss of body salt • Misdiagnosis and treatment for dehydration	• Confusion • Weakness • Nausea, vomiting	• Replace salt loss • Follow measures for heat exhaustion • If symptoms persist or become more severe with rehydration, immediate evacuation	• Follow fluid replacement guidelines • Replace lost salt by consuming meals and sports drinks, as directed. • Provide snacks or carbohydrate electrolyte beverage during long training events • Do not take dietary supplements

Note: See http://phc.amedd.army.mil for electronic versions of this document and other resources.

Figure 1.7.2-7. Commanders, Senior NCPs and Instructors Guide to Risk Management of Heat Casualties (concluded)

Recommended Readings

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Concepts

- Core body temperature (T_C)
- Electrolyte replacement
- Fighter index of thermal stress (FITS)
- Heat defense response
- Heat gain
- Heat index dhart
- Heat strain decision process
- Heat stress
- Hydration
- Hyperhydration
- Heat acclimatization
- Individual-imposed factors
- Mission-imposed factors
- Risk management
- Wet bulb globe temperature (WBGT)

Vocabulary

- Air saturation
- Air temperature
- Conduction
- Convection
- Evaporation
- Exertional heat injuries
- Heat cramps/tetany
- Heat edema
- Heat exhaustion
- Heat illness
- Heat stroke, exertional/classical
- Heat syncope
- Hyponatremia
- Miliaria rubra
- Rhabdomyolysis
- Sunburn
- Sweat rate

1.7.3. Cold Stress

1.7.3.1 Introduction.

"Environmental challenges threaten performance during an HHQ tasking. Mission: Air defense sortie to provide cover and fire support for ground forces operating in mountainous terrain. Launch was from a forward base near the AOR and only a stone's throw from the edge of the expanse of the sea. Crew was outfitted with MAC-10 flight suits, thermal gloves, and the requisite layers of flight gear including life preserver units laced to the collar of the survival vest. Loading the mission gear was uninterrupted for nearly 45 minutes; worked up a good sweat and the adrenaline of the mission sustained the heart rate through engine start, taxi, and take-off. Climbing out to the area, the sun was setting and the cabin temperature immediately began to plummet and the muscles and joints seemed to call out for more heat. First thing we noticed was how numb the hands became; there was no sanctuary from this bone chilling cold and handling any equipment that required dexterity was already a challenge. As the aircraft approached the area, the call was made to 'don the night vision goggles,' critical because the aircraft was going to 'go dark' in a few minutes. With only the NVG lighting to guide the icicles formerly called fingers, we each fumbled with the NVGs, the mounts, and toggles but finally secured the devices and switched on the frosty green glow of the tubes. Now as the aircraft motored deeper into the night, and temperature was traded for altitude, a deep chill penetrated the protective gear, every slight gap between layers became a wind tunnel to the cabin air...new problem; hypothermia began to settle in to one of the crewmen and the uncontrolled shaking could be seen across the darkened cabin..."

1.7.3.2 Cold Stressors. For the human body to maintain homeostatic balance, it must manage internal systems based upon the input of external stressors. External stressors considered to be threats to the human body consist of thermal stressors (i.e., heat, cold), odor, food, water, hypoxia, noise, light, darkness, trauma or injury, electricity, physical threats, and bacteria or viruses. With exposure to thermal stress, the human body must maintain its core body temperature (T_C) through the management of **heat loss** and heat gain. The body will either dissipate or gain heat through **convection**, **evaporation**, **conduction,** or **radiation** and generate heat through metabolism, shivering, or physical activity as shown in Figures 1.7.1-1 and 1.7.1-2. When considering the thermal stress of **cold exposure**, there are four significant **environmental variables** that must be considered: low **air temperature**, high **air movement**, high **air saturation,** and **cold water immersion** (Fig. 1.7.1-2).

Air temperature is the most obvious cold stressor; it begins to affect homeostasis of heat body balance at a temperature below T_C and skin temperature (T_{SK}). If the balance of heat loss is greater than heat production, then cold stress injuries can result, e.g., frostbite occurring when the T_{SK} reaches a range of -2°C to 0°C (28°F to 32°F) and hypothermic death with a rectal temperature of 22°C (72°F). These hypothermic conditions are a real and viable threat given the fact that some of the coldest places on earth are inhabited by humans; the coldest ambient air temperature of -87°C was recorded in 1958 at the manned Soviet Antarctic station Vostok. From an operational perspective, ascent into higher altitudes introduces reduction in air

temperatures. The **lapse rate**, i.e., air temperature decrease, is approximately -2°C (3.5°F) per 1,000 ft increase in altitude. Air movement, i.e., wind chill, increases heat loss through convection and evaporation. The most profound effect of wind chill is through the release of the still-warmed air layer trapped underneath insulated protective cold-weather clothing. Cumulatively, wind chill and evaporation on wet clothing and wet-soaked skin surface will increase heat loss when compared to air temperature alone. The National Weather Institute's **Wind Chill Chart** stratifies the risk of frostbite over time of exposure relative to air temperature plus wind chill as shown in Figure 1.7.3-1.

Wind Chill Chart

Temperature (°F)

Wind (mph) \ Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times: 30 minutes | 10 minutes | 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

Figure 1.7.3-1. National Weather Service Wind Chill Chart (11 Nov 2001)

Generally, as the wind chill index becomes increasingly more severe, the risk of frostbite increases. **Air saturation** (i.e., **humidity**, which is commonly referred to as air dryness in cold weather) is the other major cold stressor the human body must endure. With regard to saturation, cold is most often considered "dry" air because of its low water content. Cold, dry air is primarily the culprit for exercise-induced bronchial spasms (EIB), as it negatively affects the smooth muscle in the bronchial airways and lungs.

Of the four main environmental cold stressors, **cold water immersion** has the greatest magnitude of heat loss. When submerged and at rest, the body will dissipate heat approximately two to four times faster than when in air of the same temperature. Once submerged, heat loss from the body is no longer possible through evaporation, except for those body parts not submerged (i.e., the head), which can be responsible for significant heat loss. However, primary heat exchange in water immersion happens through conduction and convection with the heat-conductivity ratio of water-to-air being 24:1 with calm, stable currents creating a boundary layer around the body. By simply

changing the variable of water movement and keeping temperature constant, the body heat loss, primarily through conductance, can be up to 70 times greater than equal air temperature. The factors that affect one's survivability in addition to water temperature and movement consist of the duration of immersion, body mass, subcutaneous fat, activity level while submerged, position in the water (e.g., floating on top or submerged from the neckline down), and clothing insulation.

1.7.3.3 Physiological Response to Cold Exposure. The human body is designed to maintain a state of **thermoneutrality** wherein the body attempts to regulate T_C in response to external stressors, for example, cold stress. During periods of extreme cold exposures, the body utilizes two strategies to regulate the normal homeostatic balance of T_C: **behavioral** and **physiological temperature regulation**. Psychologically, humans will change their behavior in an attempt to conserve heat by seeking shelter, wearing cold-exposure clothing, and increasing physical activity. Physiologically, heat conservation occurs via the **primary cold-effector response** of **vasoconstriction** and **thermogenesis**.

The full spectrum of behavioral and physiological declination as hypothermic severity increases is shown in Figure 1.7.3-2. The initial physiological response to cold is a decrease in T_{SK}, which leads to vasoconstriction of subcutaneous blood flow from the skin surface to deeper tissue to maintain T_C. The vasoconstrictor response begins when T_{SK} is reduced below 35°C (95°F) and ends at approximately 31°C (88°F). The subcutaneous vasoconstriction reduces heat loss immediately by increasing skin insulation through the ß-adrenergic action of blood vessel diameter reduction and the increased plasma norepinephrine reduction in peripheral blood flow. The shunting of blood to deeper tissue reduces heat transference from blood to skin by minimizing the bloods exposure to the cold environment and thus loss of heat via conductive heat transfer. Blood flow distribution is controlled via local vasoconstrictor controls in two major regions of the body: apical and nonapical. The apical region (i.e., ears, nose, lips, hands, and feet) is primarily controlled by the adrenergic sympathetic nervous system, while the nonapical region (i.e., trunk and limbs) is regulated by the noradrenergic-active vasoconstrictor and the active vasodilator systems. The result of vasoconstrictor response to cold exposure is the stimulation of body-fluid regulation, water balance, and thoracic blood volume. With exposure to cold air, the acute effect is a 7%-15%% reduction in plasma volume and an increase in plasma osmolarity and sodium concentration. In comparison, cold water immersion reduces plasma volume by 15%-20%. **Cold-induced diuresis** can increase hemoconcentration by a twofold increase in the loss of fluid; hypotheses are still unclear.

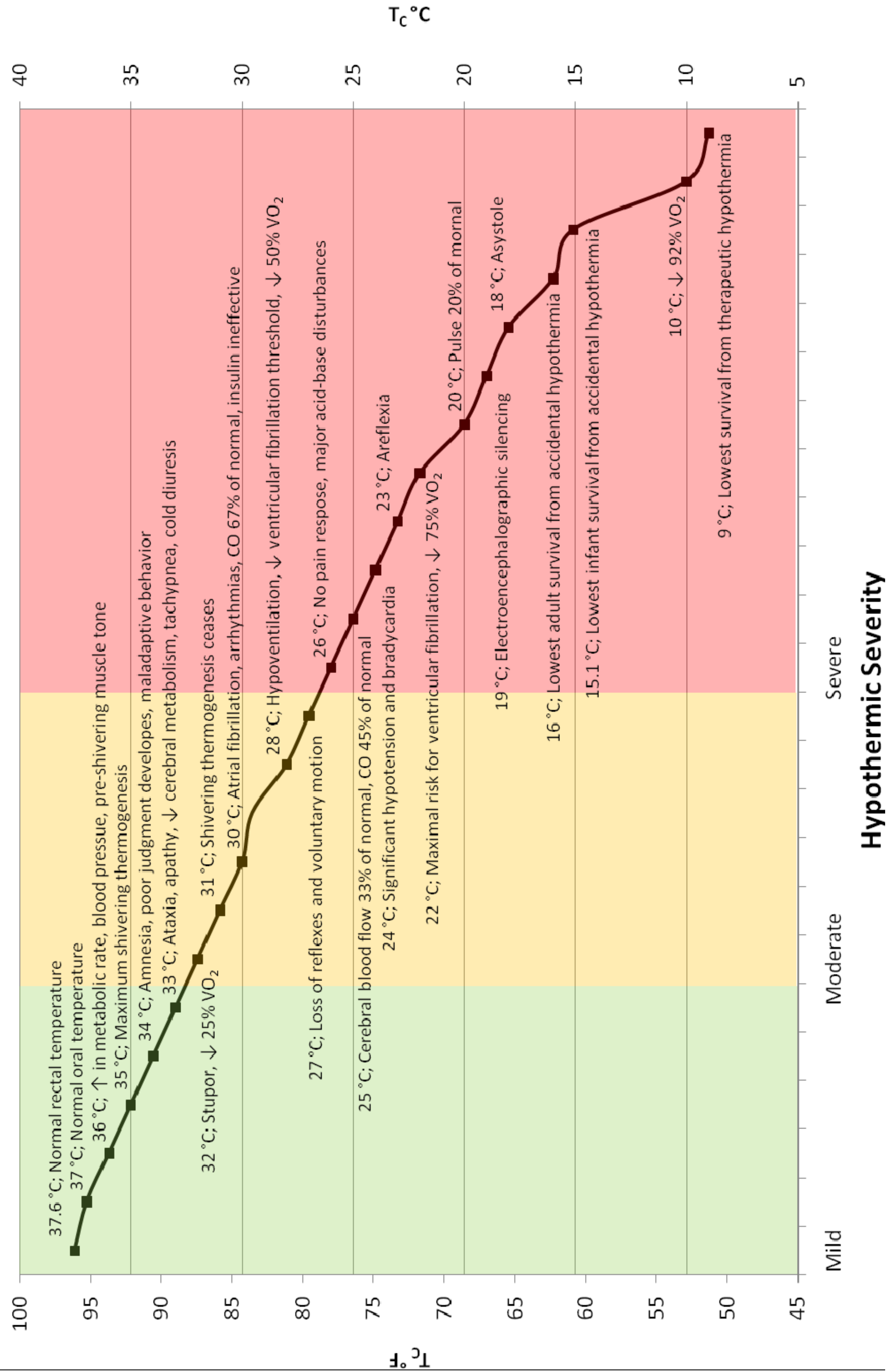

Figure 1.7.3-2. Declination of Physiological Status with Decreasing Core Body Temperature (T_c) (adapted from Table 11-1 in Pozos & Danzl, 2001)

As cold stress exposure continues, maintenance of thermoneutrality is not feasible and the rate of heat loss becomes greater than the heat generated through normal metabolism; the liberated metabolic heat can be as great as 80% of the total energy expended. Thus, thermogenesis is employed via two methods: the act of shivering and energy metabolism. **Shivering thermogenesis** is modulated via peripheral and central temperature sensors; if the T_{SK} declines and is unable to maintain T_C, then central temperature sensors are stimulated to induce a magnitude of shivering to balance the heat loss. The intensity of shivering is dependent upon T_C and T_{SK}.

For instance, if T_C is elevated prior to the reduction in T_{SK}, then the shivering thermogensis response will be less than expected. Conversely, a lower beginning T_C will enhance the thermogenic response and thus a smaller change in T_{SK} will elicit the same response. However, the significant influence T_{SK} has in shivering thermogenesis is affected in the rate of T_{SK} change. Shivering is considered to be an involuntary muscle contraction and can generate force equal to 15%-20% of maximal voluntary muscle contraction. This type of intense shivering can increase metabolic rate five to six times greater than resting metabolic rate.

Macronutrients and metabolic constituents (i.e., lipids, glucose, glycogen, and ketones), modulated through their respective metabolic processes (i.e., lipolysis, glycolysis, gluconeogenesis, glycogenolysis, and hepatic ketone metabolism), are the primary fuel sources for the human body during cold stress exposure. Generally, while at rest in a cold stress exposure, the metabolic requirements for an individual are not increased. However, metabolic demands may increase if any combinations of the following variables are experienced, for example, extreme cold (i.e., air temperature, wind chill, water immersion), intense shivering, heavy clothing, and increased work or exercise. Although the idea of limited shivering thermogenesis due to depleted carbohydrate fuel sources seems a valid notion, research has shown dietary manipulation via carbohydrate loading does not improve thermal tolerance and thus does not limit shivering thermogenesis. This is because a shift occurs from the primary metabolic fuel source of carbohydrates to that of lipid oxidation. The shift between glycolytic metabolism and lipid oxidation can be seen within 4 hr of cold exposure without significant changes to metabolic heat production and shivering thermogenesis. Additionally, during normal cold exposure there is an increase in **metabolic fuel utilization** of plasma glucose, muscle glycogen, and lipid oxidation, one and a half fold, twofold and threefold, respectively, with no change in protein usage. The percent distribution of total heat production based upon glucose, muscle glycogen, fat, and protein utilization is 10%, 30%, 50%, and 10%, respectively. Therefore, the fundamental aspects of caloric consumption and content regarding nutritional requirements for cold exposure are generally within normal dietary recommendations. However, caloric requirements are mission dependent upon additional physical activities and/or long-term, prolonged exposures to extreme cold.

The physiological response to cold water immersion is similar to cold air exposure, but with additional responses. Cold water immersion is categorized into three stages: Stage 1, Initial Immersion (0-3 min); Stage 2, Short-Term Immersion (3-15 min); Stage 3, Long-Term Immersion (≥ 30 min). Often a Stage 4, Post-Immersion, is included to address recovery. Stages 1 and 2 have the aforementioned physiological response to air plus respiratory and cardiovascular issues. Respiration may become uncontrolled, with reflex gagging and hyperventilation due to the panic response, which might result in death through aspiration or drowning. The additional cardiovascular

issue relates to the complete submersion (i.e., face and whole body) and the parasympathetic-driven, bradycardic reflex of the "diving response," also known as diving reflex; all other sympathetic responses are present. If Stage 4 is not reached, then Stages 2 and 3 of cold water immersion progress through the vasoconstriction response and shivering thermogenesis with the result of death.

1.7.3.4 Psychological Response to Cold Exposure. The physiological response to cold stress exposure is not the only variable military personnel need to be concerned about when performing operational duties: the psychological aspect of human performance is affected as well. Mission-critical duties might fail to be completed due to the decrease in morale and/or cognitive performance. Water is known to have 1,000 times greater thermal conductivity and 25 times greater heat loss when compared to cold air at the same relative temperatures. Cold water immersion has the greatest psychological performance measure decrement when compared to cold air with duration and severity being compounding variables.

The psychological response to cold exposure will often manifest before physiological changes in T_C occur, dependent upon the severity of the cold stressors. For prolonged exposure, i.e., T_C cannot be maintained at 37°C (98.6°F), the effect on psychological behavior has been compared to a level of **anesthetic impairment**, wherein consciousness and alertness decline; reflexes and responses slow; and speech is slurred, accompanied by drowsiness and apathy. As T_C drops below 35°C (95°F) towards 34°C (93°F), **memory registration** and concentration become impaired to the point of 20% loss of information from memory registration and **complex tasks processing** (e.g., mathematical calculations) decreases by approximately 17%-20%; accuracy does not seem to be affected. Auditory and visual hallucinations are not uncommon, and at a T_C of 30°C-31°C (86°F-88°F), the pupil's reflex to light may be so slow that it is misdiagnosed as absent. Deep tendon reflexes, muscle rigidity, and simple voluntary movements are difficult to control or even initiate. Most often, unconsciousness is reported between 30°C and 32°C (86°F and 90°F); however, a grunt-response to questions may occur, and failure to respond to pain-stimulus progresses to a coma state as T_C falls below 26°C (79°F). The mechanisms hypothesized for these extreme-prolonged responses to cold stress exposure consist of a slowing of synaptic gap transmission, brain cooling, changes in cerebral blood flow and electrical brain activity, as well as muscular and neuronal tissue cooling.

The mild to moderate cold stress exposure mechanism has a cumulative effect on cognitive performance through subtle effects on the central and peripheral nervous systems, which result in a decrease in human performance. A review of performance measures consists of a decrease in **manual skills** (i.e., tactile sensitivity, dexterity, strength, and motor speed), equivocal results in **vigilance**, minor changes in simple **reaction times**, significant increase in **complex-tasks choice reaction time**, significant impairment of **memory recall**, and complex cognitive functioning decrement due to task complexity. Ultimately, an individual's behavior and decision-making ability are based upon the subjective perception and evaluation of his/her surroundings more so than the objective evaluation of exposure time, physiological status, prior acclimatization, or core body temperature.

1.7.3.5 Self-Imposed Factors Effect on the Physiological Response to Cold Exposure. There are a few major individual- and mission-imposed factors that affect a person's ability to respond to cold stress exposure. **Individual-imposed factors**

pertain to a person's physiological status and abilities that are not under the immediate-direct control of the individual. Conversely, **mission-imposed factors** can be considered as variables outside the body that an individual does have immediate-direct control over and can change with minimal effort to aid in the response to cold exposure. The individual factors consist of anthropometric measures (i.e., body size, subcutaneous fat), gender, ethnicity, physical fitness, and age, while the mission factors pertain to physical fatigue, dehydration, nutrition, alcohol, and nicotine.

Of the individual-imposed factors, anthropometric measurement (i.e., body size, subcutaneous fat) is the factor with the greatest variability to an individual's cold exposure response. Individuals with a long and lean body size (i.e., ectomorph) have a high body surface area to body mass ratio, thus losing more heat than their short and stocky counterparts (i.e., mesomorph). The following is true because the ectomorph has an increased convective heat loss due to greater transference via skin surface. The insulative property of subcutaneous fat adds an additional layer of protection that is inverse heat loss; thus, the greater the layer of subcutaneous fat the less heat loss from the body and a reduction in shivering thermogenesis. However, this should not promote total body weight gain from total fat tissue. The similar thermal resistance is exhibited in a person with increased lean muscle mass due to the additive vasoconstriction of blood flow to the skin and muscle, creating an improved insulative layer. Complementary to the improved insulative layer is the improved shivering thermogenesis due to a greater muscle mass when compared to the ectomorph. Gender, ethnicity, and physical fitness all relate to the anthropometric measurements and the resultant effect on an individual's cold exposure response. Gender differences are attributed to the female's greater body fat percentage and thicker subcutaneous fat layer when compared to a male the same age and weight. Ethnicity uses the same logic as gender differences. The relationship of physical fitness is based upon body composition differences and sustainable steady-state activity between fit and less fit individuals. Age, greater than 45 yr, affects cold exposure response due to the declination in physical fitness and reduced vasoconstrictor response.

Mission-imposed factors affect an individual's response through his/her own specific methods and are commonly associated with military operations in extreme environments. Physical fatigue reduces shivering thermogenesis and vasoconstrictor response, resulting in a reduction in sustainable steady-state activity, thus reducing the ability to maintain T_C. Dehydration increases the susceptibility to cold stress injuries by reducing the sustainable steady-state activity as well. Poor nutrition can lead to a diminished glucose and glycogen availability, which can reduce the central nervous system modulated aspect of shivering thermogenesis and the peripheral heat production. The risk of hypothermia due to the reduction in shivering thermogenesis increases when a person is without food for more than 48 hr. The primary concern with consumption of alcohol focuses on peripheral vasodilation and the concomitant heat loss. In addition, alcohol can cause hypoglycemia, reducing the shivering thermogenesis response and the ability to sustain physical activity, as well as a false perception of warmth. Conversely, the vasoconstrictor response to nicotine consumption is of primary concern in cold stress exposure. Nicotine from "heavy" smoking (e.g., two-three packs per day) or chewing tobacco increases a person's susceptibility to freeze-related injuries because of the vasoconstriction of peripheral blood flow.

1.7.3.6 Acclimatization to Cold Exposure. The resultant outcome of exposure to thermal stress is **acclimatization**; however, acclimatization to cold stress is less apparent when compared to heat stress acclimatization. The modest human pattern of acclimatization to cold stress (Fig. 1.7.3-3) that an individual will undergo is dependent upon the nature and severity of the exposure (i.e., intensity, frequency, duration, and mode). There are three physiological adaptive mechanisms an individual might undergo in response to cold stressor exposure: habituation, insulative, and metabolic acclimatization. **Habituation**, the first and most common type of cold exposure acclimatization, is exemplified by the diminished physiological response to cold exposure of individuals with exposure versus those without exposure. Individuals who are habituated to cold exposure often show signs of reduced vasoconstrictor and shivering thermogenesis responses; they may also exhibit a higher peripheral T_{SK}, improved cold-induced vasodilation (CIVD) response, decreased sense of pain, and improved manual dexterity skills. Cold habituation can further be divided into two subcategories: short-term and long-term exposures. Short-term exposure is considered less than 1 hr per exposure a few times per week, producing habituation. Long-term exposure is the physiological response to 8 hr or more of moderate-cold exposure on successive days for a period of 2 wk or more. The resultant effect of long-term exposure is known as hypothermic habituation, and those with long-term cold habituation may display a more pronounced reduction in T_C when compared to noncold-habituated individuals.

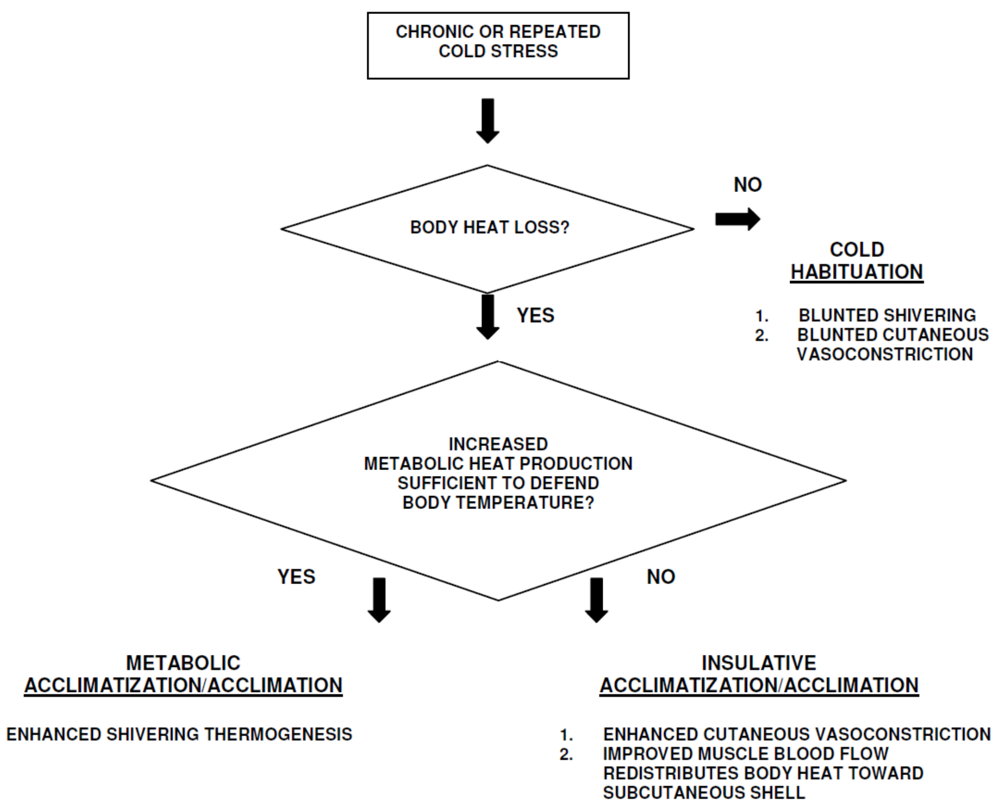

Figure 1.7.3-3. Human Pattern of Cold Acclimatization

The second possible mechanism of physiological adaptation concerns heat conservation through **insulative acclimatization**. After several weeks of repeated cold exposures, an improved vasoconstrictor response due to a more rapid sympathetic nervous system response drops the T_{SK} faster, thus decreasing skin thermal conductance. Convective heat loss through an improved countercurrent heat exchange is postulated to be a factor for insulative acclimatization. Individuals who have an acclimatized insulative physiological mechanism to cold stressors may also exhibit a lower resting T_C. The third physiological mechanism to cold stress exposure has not been unequivocally proven regarding **metabolic acclimatization**. Exaggerated shivering may be seen in individuals exposed to chronic cold, thus increasing heat production via shivering thermogensis. However, the theory of increased heat production through metabolism, nonshivering thermogenesis, has not been unequivocally proven. The operational benefit of cold stress acclimatization, i.e., habituation, insulative, and metabolic mechanisms, consists of improving the ability to perform motor skills, increasing thermal comfort, increasing CIVD responses, and reducing susceptibility to cold injury in an overall effort to improve human performance. With regard to the acclimatization factors for psychological aspects, preliminary research reports that cold-climate training improves performance of manual skills, but future research should focus on those tasks vulnerable to cold stressor exposure distractions.

1.7.3.7 Medical Considerations. There are seven **cold stress injuries** that commonly occur: hypothermia, chilblain, pernio, trench foot, immersion foot, frostnip, and frostbite. The diagnosis and treatment of these injuries are important but are beyond the scope of this manual; professional licensure should perform such functions. However, the recognition and prevention of these conditions are of relevance and will be discussed.

Hypothermia, the most widely known cold exposure injury, is defined by a -2°C (3.5°F) drop in T_C from the normal 37°C to 35°C (98.6°F to 95°F), the most commonly agreed upon definition. The onset of hypothermia will differ by case due to the variability in the conditions of the operational and ambient environments and the variability in the person's individual factors (e.g., age, fitness, and percent body fat). The best way to avoid getting hypothermia is to understand the common factors leading up to the onset as well as the signs and symptoms. There are two common factors that contribute to the onset of hypothermia: wet clothes and extended periods of exposure to the cold or any combination thereof. If one is unable to minimize the risk of hypothermia, then recognition of the signs and symptoms aid in the prevention and early detection. The signs and symptoms include shivering, grayish skin color, vague/slow/slurred speech, argumentativeness, irritability, immobile fingers, impaired motor skills, difficulty walking, drowsiness, and fatigue.

Of lesser severity are the cold exposure, nonfrozen injuries of chilblain and pernio. Both have similar causes of onset and pathology and present mostly in the hand, toes, legs, and ears of children, women, and women of middle age. **Chilblain** is seen between temperatures of 0.5ºC-16ºC (33°F-61°F) and is the result of cold-induced vasoconstriction that causes cell ischemia and limb edema. White blood cells are transported into deep tissue, causing swelling of the tissue and blood vessels, which leads to the manifestation of red skin or plaques that may blister or ulcer. **Pernio** is the next progression of chilblain; patches of dead skin are peeled off, while superficial burning and pain replace the milder symptoms of chilblain. An indirect protective

mechanism against cold-induced vasoconstriction blood flow reduction is the CNS-modulated, vasomotor cold-induced vasodilation. In response to the decrease in T_{SK}, CIVD will allow periodic increase of blood flow to the periphery, resulting in an oscillator T_{SK} response over time. Preexisting medical conditions such as diabetes and Raynaud's syndrome or mission-imposed conditions with vibrations blunt the CIVD response, which might increase the risk of these cold injuries.

Trench foot and **immersion foot** are slightly more severe, nonfrozen injuries. Trench foot is considered to be the next progression of untreated, undiagnosed pernio. Trench and immersion foot distinction can be difficult because on the similarities in the onset and pathology. Both develop slowly over a period of hours to days due to an overexposure of wet feet to temperatures between 0.5°C and 10°C (33°F and 50°F) for more than 12 hr. The cause of the injuries is vasoneuropathy, which is damage to the nerve and blood vessels without the freezing of water in the tissue. Immersion foot starts off with the area being cold, swollen, or numb for a few days, followed by a 2- to 6-wk period where blood vessels are destroyed, blistering or ulcerations appear, and/or significant temperature changes occur – all without a pulse. Finally, within a few months the affected area may present with no signs or symptoms; Raynaud's disease may develop or there may be signs of itching, pain, swelling, or lack of sensation. Trench foot occurs on land and from exposure to wet footgear, malnutrition, and indifference. Ultimately, the loss of the limb or leg may be imminent.

Frostbite, considered to be a freezing injury, has three classifications: frostnip, superficial frostbite, and severe frostbite. **Frostnip**, lesser in severity, is considered to be a first-degree skin burn usually imposed by super-cooled liquid or metal and wind chill exposure. There may be some redness and peeling of skin, similar to a sunburn. **Superficial frostbite** is more severe and involves the burning of the full skin layer and tissue underneath. The area will appear white-gray with the superficial skin layer being tough and the tissue just beneath being soft-spongy with blisters appearing within 24 hr. **Severe frostbite** consists of tissue death due to freezing and crystallization of water within the tissue. Slow cooling of the tissue will produce the lesser of the damage because rapid cooling will form intracellular crystals, rupturing the cells, while slow cooling forms interstitial crystals without cellular rupture. Most of the damage is vascular in nature from the formation of blood clots, fibrin deposits in the arteriole walls, cell hypoxia, and vascular wall degradation. The affected area is often described as seemingly like a third-degree skin burn. The causes of severe frostbite are the same as for frostnip and superficial frostbite: temperature, wind chill, exposed skin, moisture in clothing against skin, poor insulation, direct skin contact with super-cool liquid or metal, cramped position, tight clothing or boots, dehydration, and localized pressure. The three compounding factors leading to these freezing injuries are cigarette smoking, mental and physical fatigue, and lengthy periods of time without body movement. The onset of hypothermia and freezing and nonfreezing cold injuries is of significant concern when considering cold stress exposure in the operational environment. The best method of avoiding these injuries is not the diagnosis, or prognosis or treatment, but rather the recognition and even more so prevention.

1.7.3.8 Prevention. Prevention of cold stress exposure injuries can be best confronted with preparation through training, nutrition and hydration, proper clothing, and proper management of time of exposure. Of course, knowledge of the signs and symptoms is necessary in the early recognition of potentially hazardous situations and environmental conditions that result in minor to severe injury or even death.

In cold environment training, physical training is one of the most important factors promoting prevention of injury or death. People who are physically fit have greater abilities to control their thermoregulatory system, greater metabolic heat production, and T_C maintenance insulation via constriction. Physical training has also been shown to offset the deleterious effects of wind chill in two ways. The first is through an increase muscle mass activation, which can provide greater heat production during shivering thermogenesis when compared to untrained people. Secondly, metabolic heat production can reach higher levels for longer periods of time due to a physically fit person's ability to perform greater workloads that are sustained for longer periods because of the person's greater work capacity (i.e., VO_2 max). Individuals who are physically fit have greater capability of keeping their extremities from cooling too quickly. Training in cold weather environments to better acquaint personnel with the interaction between themselves; their physical knowledge, skills, and abilities (i.e., KSAs); the equipment; and situational awareness is important. Practice maneuvers relative to the operational environment will improve those training KSAs.

The potential nutritional intake in an operational environment that accounts for maximal physical activity in addition to exposure to cold stress may be as high as 4,500 kcal per day. Hot meal requirements have been suggested in 10-day rotations: the first 10 days, one hot meal; the second 10 days, one hot-wet meal per day; the third 10 days, two hot-wet meals per day. The other meals are provided through Meal, Ready-to-Eat (MRE) rations. Along with MRE meals, additional water is required; thus, at least 4 qt of water should be consumed each day per person. Recall, water is the most important survival requirement in an environment with exposure to cold stressors; therefore, extra care must be taken to make certain sufficient water intake is achieved when factoring level of physical activity and extra diuresis due to nutritional, supplemental, or medication ingestion.

The time must be taken prior to any cold stress exposure to be properly fitted with appropriate cold-weather clothing. Airmen should be outfitted with multilayer clothing, and each item must be fitted individually to the airman's anthropometric measurements in an effort to optimize comfort and fit. With well-fitted, multilayer clothing, airmen are able to contain air close to the body, warm the air with their own natural body heat, and then keep the warm air close to the body while simultaneously keeping perspiration away from the skin. The overall idea is to be able to take off and put on multiple layers of clothes dependent upon the environment without letting the warm, trapped air out or the cold, moist air in. The layering of clothing is a simple concept; consider the three basic "Ws," wicking, warming, and weathering. The wicking layer keeps moisture away from the skin and should be some type of polysynthetic material; cotton has a tendency to hold moisture and will keep it close to the skin, reducing thermal aspects of warming the layer of air as well as putting the airman at risk of freezing the cotton layer to the skin if exposed to the appropriate environment. The warming layer is just that, a looser layer of clothing, atop the whisking layer, that is meant to optimize the warming of air closest to the body. One of the best warming layers is a tightly knitted wool; just be careful not to get wool wet or it will trap cooler moisture closer to the body and reduce its thermal effect. Finally, the weathering layer's purpose is to aid in protecting you from the harsh cold environment while keeping another layer of warm air on top of the warming layer of air. The weathering layer is mainly for protection of the warming layers. Boots must fit properly, not too snug, so try them on with all variations of socks provided. If the toes are too tight, then get a larger size boot. Remove and dry socks and boots two to three times per day to

prevent trench foot; do not sleep with footwear on. The variables one must consider when selecting clothing requirements should focus on higher insulation values for more extreme environments. Additionally, military personnel must take into account the type of material they might encounter (i.e., air, wood, stone, steel, aluminum) and its respective thermal conductance in relation to skin-to-material time of exposure. These factors, individual- and mission-imposed stresses, all play a significant role in the overall outcome/result of a given scenario, whether training or in the real world.

Ultimately, unit leadership is responsible for training and its proper implementation. The U.S. Army Center of Health Promotion and Preventive Medicine has distributed a cold risk manual that outlines a five-step risk management tool with the intent of preventing cold causalities (Fig. 1.7.3-4). The first step is to identify the hazards, such as weather conditions, inventory of required supplies, and self-imposed factors. The second step of hazard assessment focuses on the proper use of wind chill index charts relating to environmental conditions, work intensity, food and clothing, and injuries stratified into risk categories. The development of control points establishes limits for the third step. The implementation, supervision, and evaluation of the risk management plan are the final steps of the process, steps four and five. The cold exposure risk management tool is only effective if it remains as a dynamic loop that continues to take into account the ever-changing variables of the ambient environment, military personnel, and operational mission. Situational awareness is paramount when military personnel perform active and nonactive duties in cold environments, and if the proper preventive measures are implemented, cold exposure injuries such as hypothermia and frozen and nonfrozen injuries are preventable. Prevention begins in pretraining preparation; use of wind chill charts to manage personnel time of exposure to the cold environment; risk assessment by medical personnel on active duty personnel; an established buddy system to advise one another in early detection of hazardous factors; and, most importantly, with leadership, leading by example.

Unit Leaders' and Instructors' Risk Management Steps for Preventing Cold Casualties

Risk Management is the Process of Identifying and Controlling Hazards to Protect the Force

Possible Outcomes of Inadequate Climatic Cold

- **Chilblain** (due to bare skin exposed to cold humid air)
- **Immersion Foot (Trench Foot)** (due to wet feet)
- **Frostbite**
- **Hypothermia** (whole body temperature dangerously low)
- **Dehydration**
- **Snow Blindness**
- **Carbon Monoxide Poisoning**

The Five Steps of Risk Management Are:

1 Identify Hazards

- Cold (temperature 40° F and below)
- Wet (rain, snow, ice, humidity) or wet clothes
- Wind (wind speed 5 mph and higher)
- Lack of adequate shelter/clothing
- Lack of provisions/water
- Other Risk Factors include:
  - Previous cold injuries or other significant injuries
  - Use of tobacco/nicotine or alcohol
  - Skipping meals/poor nutrition
  - Low activity
  - Fatigue/sleep deprivation
  - Little experience/training in cold weather
  - Cold casualties in the previous 2-3 days
  - Overly Motivated Soldiers

2 Assess Hazards

Follow the Wind Chill Temperature Table to Determine the Danger Level

Do individuals have adequate shelter/clothing?

- Are clothes clean without stains, holes or blemishes (which could decrease heat-retaining function)?

Have meals been consumed?

- Are meals warm?

Are there other circumstances?

- Is there contact with bare metal or fuel/POL (petroleum, oils or lubricants)?
- Is the environment wet? Is there contact with wet materials or wet ground?
- Can soldier move around to keep warm?
- Are feet dry and warm?
- Is the soldier with a buddy who can assist/watch over to prevent cold injures?

Figure 1.7.3-4. U.S. Army Center for Health Promotion and Preventive Medicine Five-Step Cold Risk Management Tool

2 Assess Hazards continued

Using the Wind Chill Temperature Table

The wind chill index (see table below) gives the equivalent temperature of the cooling power of wind on exposed flesh.

- Any movement of air has the same effect as wind (running, riding in open vehicles, or helicopter downwash).
- Any dry clothing (mittens, scarves, masks) or material which reduces wind exposure will help protect the covered skin.

Trench foot injuries can occur at any point on the wind chill chart and -

- Are much more likely to occur than frostbite at "LITTLE DANGER" wind chill temperatures, especially on extended exercises/missions and/or in wet environments.
- Can lead to permanent disability, just like frostbite.

Wind Chill Temperature Table

Air Temperature (°F)

Wind Speed (mph) ↓	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
0	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95

GREEN LITTLE DANGER (frostbite occurs in >2 hours in dry, exposed skin)
YELLOW INCREASED DANGER (frostbite could occur in 45 minutes or less in dry exposed skin)
RED GREAT DANGER (frostbite could occur in 5 minutes or less in dry, exposed skin)

Wind Chill Category (see Wind Chill Temperature Table above)

Work Intensity	Little Danger	Increased Danger	Great Danger
High Digging foxhole, running, marching with rucksack, making or breaking bivouac	Increased surveillance by small unit leaders; Black gloves optional - mandatory below 0°F (-18°C);	ECWCS* or equivalent; Mittens with liners; No facial camouflage; Exposed skin covered and kept dry; Rest in warm, sheltered area; Vapor barrier boots below 0°F (-18°C) Provide warming facilities	Postpone non-essential training; Essential tasks only with <15 minute exposure; Work groups of no less than 2; Cover all exposed skin, Provide warming facilities
Low Walking, marching without rucksack, drill and ceremony	Increased surveillance; Cover exposed flesh when possible; Mittens with liner and no facial camouflage below 10°F (-12°C); Full head cover below 0°F (-18°C). Keep skin dry - especially around nose and mouth.	Restrict Non-essential training; 30-40 minute work cycles with frequent supervisory surveillance for essential tasks. See above.	Cancel Outdoor Training
Sedentary Sentry duty, eating, resting, sleeping, clerical work	See above; Full head cover and no facial camouflage below 10°F (-12°C); Cold-weather boots (VB) below 0°F (-18°C); Shorten duty cycles; Provide warming facilities	Postpone non-essential training; 15-20 minute work cycles for essential tasks; Work groups of no less than 2 personnel; No exposed skin	Cancel Outdoor Training

*ECWCS – Extended Cold Weather Clothing System

Note: These guidelines are generalized for worldwide use. Commanders of units with extensive extreme cold-weather training and specialized equipment may opt to use less conservative guidelines.

Figure 1.7.3-4. U.S. Army Center for Health Promotion and Preventive Medicine Five-Step Cold Risk Management Tool (continued)

3

Develop Controls

Main Points to Stress to Soldiers

When using Cold-Weather Clothing, Remember . . .

C-O-L-D

Keep it………	**C**lean
Avoid……….	**O**verheating
Wear it…….	**L**oose in layers
Keep it ……..	**D**ry

Main Points to Stress to Leaders

Follow these Wind Chill Preventive Medicine Measures
Based on Wind Chill Temperature

30°F and below	Alert personnel to the potential for cold injuries
25°F and below	Leaders inspect personnel for wear of cold weather clothing. Provide warm-up tents/areas/hot beverages.
0°F and below	Leaders inspect personnel for cold injuries. Increase the frequency of guard rotations to warming areas. Discourage smoking.
-10°F and below	Postpone non-essential outdoor training. For mission essential operations, initiate the buddy system - Have personnel check each other for cold injuries.
-20°F and below	Consider modifying or curtailing all but mission-essential field operations.

NOTE: Trench Foot can occur at any temperature - Always Keep Feet Warm

General Guidance for all Cold-Weather Training

Skin: Exposed skin is more likely to develop frostbite, therefore cover skin. Avoid wet skin (common around the nose and mouth). Inspect hands, feet, face and ears frequently for signs of frostbite.
Clothing: Soldiers must change into dry clothing at least daily and whenever clothing becomes wet. Soldiers must wash and dry feet and put on dry socks at least twice daily.
Nutrition: 4500 calories / day / soldier. Equivalent to 3 meal packets in meal-cold weather (MCW) or 3-4 MREs.
Hydration: 3-6 liters (canteens) / day / soldier. Warm, sweet drinks are useful for re-warming.
Camouflage: Obscures detection of cold injuries; consider not using below wind chill of 32° F; not recommended below wind chill of 10°F.
Responsibilities: Soldiers are responsible for preventing individual cold injuries. Unit NCOs are responsible for the health and safety of their troops.
Cold injury prevention is a command responsibility.

Figure 1.7.3-4. U.S. Army Center for Health Promotion and Preventive Medicine Five-Step Cold Risk Management Tool (continued)

3 Develop Controls continued

Personal Protection

Ensure Appropriate Clothes and Proper Wearing of Clothes –

- Wear clothing loose and in layers.
- Ensure all clothing is clean.
- Ensure proper boots are worn and are dry.
- Ensure clothes do not have holes, broken zippers, etc.
- Ensure hands, fingers, and head are covered and protected.
- Avoid spilling liquids on skin or clothes. Liquid stains will reduce clothing's protective efforts.
- Change wet, damp clothes ASAP.

Keep Body Warm

- Keep moving.
- Exercise big muscles (arms, shoulders, trunk, and legs) to keep warm.
- Avoid alcohol use (alcohol impairs the body's ability to shiver).
- Avoid standing on cold, wet ground.
- Avoid all tobacco products (they decrease blood flow to skin).
- Eat all meals to maintain energy.
- Drink water or warm non-alcoholic fluids to prevent dehydration.

Protect Feet

- Keep socks clean and dry.
- Wash feet daily, if possible.
- Carry extra pairs of socks.
- Change wet or damp socks ASAP; use foot powder on feet and boots.
- Avoid tight socks and boots; do not over-tighten boot or shoes.
- Wear overshoes to keep boots dry.

Protect Hands

- Wear gloves, mittens, or gloves/mittens with inserts.
- Warm hands under clothes if they become numb.
- Avoid skin contact with snow, fuel or bare metal. Wear proper gloves when handling fuel or bare metal.
- Waterproof gloves by treating with waterproofing compounds.

Physical Fitness Uniform

- Wind Chill >60 deg F: T-shirt and trunks
- Wind Chill 51-60 deg F: Add jacket
- Wind Chill <50 deg F: Add pants, cap, gloves

Figure 1.7.3-4. U.S. Army Center for Health Promotion and Preventive Medicine Five-Step Cold Risk Management Tool (continued)

3 Develop Controls continued

Personal Protection continued

Protect Face and Ears
- Cover face and ears with scarf. Wear insulated cap with flaps over ears or balaclava.
- Warm face and ears by covering them with your hands. Do NOT rub face or ears.
- Consider not using face camouflage when wind chill is 32° F or below. Also not recommended below 10° F.
- Wear sunscreen.
- Exercise facial muscles.

Protect Your Eyes
- Wear sunglasses to prevent snow blindness.
- If sunglasses are not available, protective slit goggles can be made from cutting slits in cardboard (e.g., MRE cardboard box).

Protect Each Other
- Watch for signs of frostbite and other cold weather injuries in your buddy.
- Ask about and assist with re-warming of feet, hand, ears or face.

Prevent Carbon Monoxide Poisoning
- Use only Army-approved heaters in sleeping areas. (post Fire Guards)
- Do not sleep near exhaust of a vehicle while vehicle is running.
- Do not sleep in enclosed area where an open fire is burning.

Leadership Controls

- Discontinue/limit activities/exercise during very cold weather (see chart page 2).
- Use covered vehicles for troop transport.
- Have warming tents available. (with Fire Guards)
- Have warm food and drink on hand.

Facility Controls

- Use only Army-authorized heaters. (i.e., no kerosene or propane heaters).
- Ensure heaters are in working order and adequately ventilated.
- Ensure integrity of shelters for maximum protection from the cold.

Figure 1.7.3-4. U.S. Army Center for Health Promotion and Preventive Medicine Five-Step Cold Risk Management Tool (continued)

4 Implement Controls

- Identified controls are in place
- Controls are integrated into SOPs
  - Educate soldiers of hazards and controls (including newly arrived soldiers)
  - Implement buddy system to check clothes/personal protection
- Decision to accept risk is made at appropriate level
- Buddy system to check each other
- Self checks
- Lip Balm (for high altitude training)

5 Supervise and Evaluate

- Ensure all soldiers are educated about prevention, recognition and treatment of cold weather injuries.
- Delegate responsibilities to ensure control measures have been implemented.
- Monitor adequacy/progress of implementation of control measures.
- Do frequent spot checks of clothes, personal protection and hydration.
- Record and monitor indicators of increasing cold risks, for example:
  - Increasing number of cold weather injuries
  - Increased complaints/comments about cold
  - Observations of shivering, signs of cold weather injuries
- Evaluate current control measures and strategize new or more efficient ways to keep warm and avoid cold injuries

2002

Note: See http://phc.amedd.army.mil for electronic versions of this document and other resources.

Figure 1.7.3-4. U.S. Army Center for Health Promotion and Preventive Medicine Five-Step Cold Risk Management Tool (concluded)

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Concepts

- Acclimatization
- Anesthetic impairment
- Behavioral temperature regulation
- Cold-induced diuresis
- Cold stressor injuries
- Habituation acclimatization
- Insulative acclimatization
- Individual-imposed factors
- Lapse rate
- Metabolic fuel utilization
- Metabolic acclimatization
- Mission-imposed factors
- Physiological temperature regulation
- Prevention
- Primary cold-effector response
- Shivering thermogenesis
- Thermogenesis

Thermoneutrality
Vasoconstriction

Vocabulary

Air movement
Air saturation
Air temperature
Chilblain
Complex tasks processing
Complex tasks choice reaction time
Conduction
Convection
Core body temperature (T_c)
Evaporation
Frostbite
Frostnip
Hypothermia
Immersion foot
Manual skills
Memory recall
Memory registration
Prevention
Radiation
Reaction times
Shivering thermogenesis
Severe frostbite
Superficial frostbite
Trench foot
Vigilance
Water immersion
Wind chill chart

2. ATMOSPHERE

James T. Webb, Ph.D.

Variation in earth-bound environmental conditions places limits and requirements on our activities. Even at sea level, atmospheric environmental conditions vary considerably due to latitude, climate, and weather. Throughout the range of Air Force operations, crewmembers and their craft face even larger variations in atmospheric properties that require life support systems and personal equipment for survival and preservation of optimal function. Understanding the physical nature of our atmosphere is crucial to understanding how it interacts with human physiology and what protective measures must be employed.

The evolution of humans on the surface of the earth did not involve selection of traits for survival and optimal performance above the altitudes where most humans and their predecessors resided. Most humans lived at or near sea level throughout history. Our species typically lacks significant permanent adaptations to high altitude. Therefore, we exhibit significant and progressively reduced performance when exposed to altitudes above 10,000 ft. The effects covered here are acute. They occur over relatively short periods of exposure and are pertinent to the altitude exposures typical during Air Force missions. Other deleterious effects of altitude are slower to develop (e.g., high altitude pulmonary edema, acute mountain sickness). However, these usually will not have time to develop in a typical Air Force flying mission.

2.1. Constituents and Properties of the Atmosphere

In 1805 John Dalton provided the first analysis of the constituents of the atmosphere by percentage of each gas (Dalton, 1805).

2.1.1. Constituents of the Atmosphere

Discussion of the atmosphere as a whole required development of a definition of a standard atmosphere. The standard atmospheric pressure *at sea level is accepted to be 760 mmHg, which is equivalent to 14.7 psi and 29.92 inHg at 15^{o}C (59^{o}F).*

Constituents of the atmosphere we breathe are shown in **Table 2.1.1-1** and these percentages are consistent throughout the atmosphere of interest to aerospace physiology. However, as altitude increases, the total pressure decreases yielding a decrease in partial pressure of each of the constituents of the atmosphere.

2.1.2. Atmospheric Zones

Two strategies for dividing the atmosphere into zones are presented here. The first and most generally used is based on physical characteristics of the atmosphere itself. The second is more useful to the aerospace physiologist and is based on the physiological needs of humans.

Table 2.1.2-1. Constituents of Earth's Atmosphere[a]

Gas	Atmospheric Content (%)	Partial Pressure (mmHg)
Nitrogen	78.084	593.44
Oxygen	20.948	159.20
Argon	0.934	7.10
Carbon dioxide	0.031	0.24
Other gases	0.003	0.02
Total	100.000	760.00

[a]Clean, dry air at 15°C (59°F), sea level; mean of values every 15° between 15° N and 75° N (U.S. Standard Atmosphere, 1962)

Temperature and its lapse rate, direction and rate of change with respect to altitude, provide much of the basis for subdivisions of Earth's atmosphere into regions as defined in Figure 2.1.2-1.

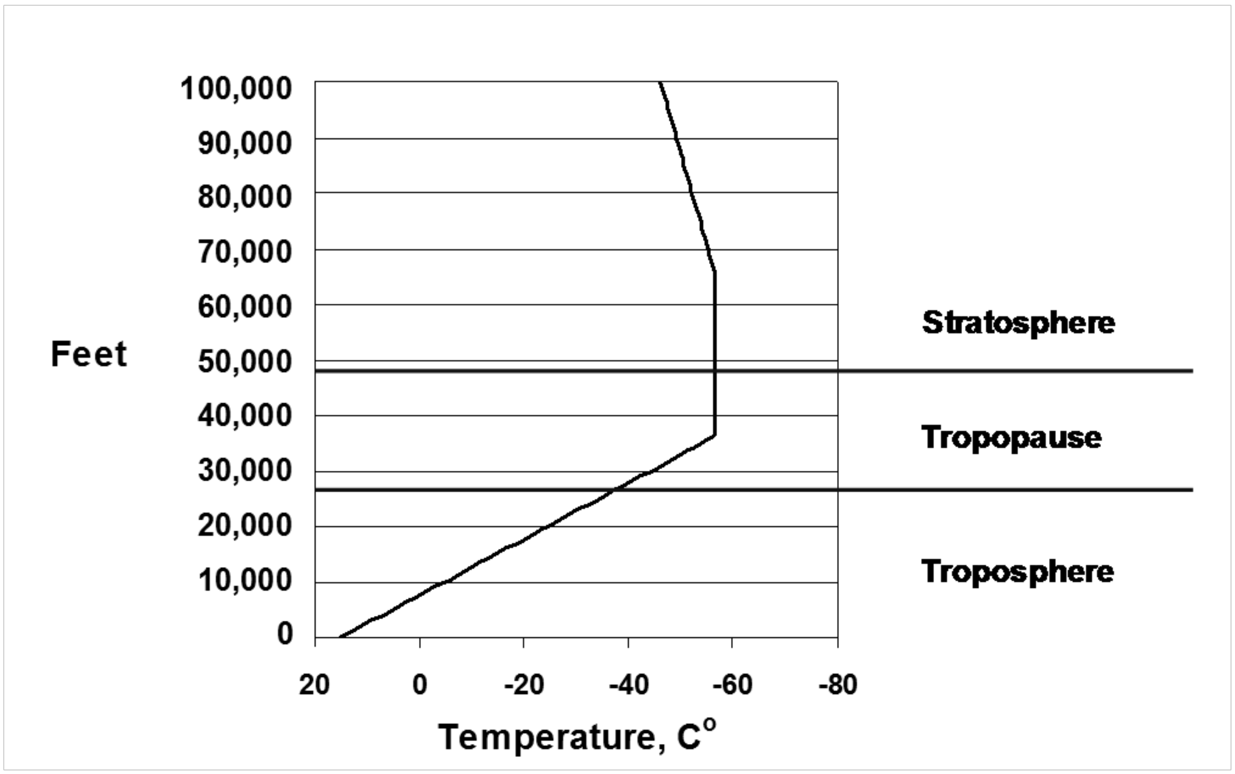

Figure 2.1.2-1. Zones of Earth's Atmosphere

The lowest zone, the troposphere, is the only region of Earth's atmosphere capable of supporting human habitation without artificial support. The troposphere starts at the Earth's surface and extends to the tropopause**,** between 26,000 and 48,000 ft (5-9 mi, 8-14.5 km) higher at the equator and lower at the poles. At its higher levels, above 20,000 ft (3.8 mi, 6 km), at least some degree of artificial support is required in the form of supplemental oxygen. A linear decrease in temperature characterizes the troposphere from sea level (15°C) to the tropopause, typically at about 35,000 ft (6.6 mi, 10.7 km), where the temperature is normally about –55°C. The lapse rate is -2°C or about -3.5°F per 1,000 ft.

Approximately 80% of the mass of the atmosphere and most of the weather phenomena occur in the troposphere.

Variations in temperature, pressure, and humidity in the troposphere account for extreme differences in the environmental conditions we experience as weather.

The tropopause is the division between the troposphere and stratosphere. Aircraft jet engines perform with greater efficiency at lower temperatures, which is one reason cruise is planned near the tropopause where the temperature is lowest. The stratosphere starts just above the tropopause and extends up to 164,000 ft (31 mi, 50 km). Ninety-nine percent of the mass of the air is located in the troposphere and stratosphere. The temperature throughout the lower part of the stratosphere is relatively constant (Fig. 2.1.2-1). Compared to the troposphere, this part of the atmosphere is dry and less dense. The temperature in this region increases gradually to -3°C, as the absorption of ultraviolet radiation creates a positive lapse rate.

Ultraviolet radiation reaching the lower stratosphere from the sun is responsible for the creation of ozone, the ozone layer, or ozonosphere. In the process of ozone production and in reactions with ozone, nearly all of the ultraviolet (UV) radiation is absorbed, including the most hazardous form to life forms, UV-C. Much of UV-B is also absorbed, although the UV-B reaching the surface is sufficient to be a major cause of sunburn and melanoma cancers. Most of the UV-A reaches the Earth's surface. UV-A converts a precursor to vitamin D in human skin. Although flight in the upper troposphere and lower stratosphere involves exposure to more radiation than on the surface, no health risk is currently associated with routine flying operations. Flight above the stratosphere and space flight involve risk of exposure to significant levels of radiation.

The higher regions of the atmosphere, 50,000 ft and above, are so thin that pressure suits are required to sustain life. Temperature variations result from variable absorption of the sun's energy in several forms; hence, thermal protection must be incorporated for any exposure in these regions. In the higher regions, flight of "air-breathing" aircraft (those that use atmospheric oxygen to burn fuel) becomes impossible and control surfaces are no longer effective.

Refer to the references and recommended reading for further information.

Another typical subdivision of the atmosphere described above relates to the ability of humans to function based on the partial pressure of oxygen available and the need for artificial pressure to sustain life. These divisions are refered to as the physiological divisions of the atmosphere and are described in Table 2.1.2-2 below.

Table 2.1.2-2. Physiological Divisions of the Atmosphere

Physiological Division	Altitude and Pressure Range	Problems	Solutions
Physiological Zone	0-10,000 ft 0-3,048 m 760-523 mmHg	Trapped gas expansion/contraction during changes in pressure results in middle ear or sinus blocks; shortness of breath, dizziness, headache, or nausea in unacclimatized individuals or with exercise	Reductions in performance or longer term acclimatization
Physiologically Deficient Zone	10,000-50,000 ft 3,048-15,240 m 523-87 mmHg	Oxygen deficiency progresses from minor reductions in cognitive and physical capabilities at 10,000 ft to death over about 25,000 ft (possibly lower) without supplemental oxygen	Supplemental oxygen allows good performance to about 35,000 ft with progressively less capability
Space Equivalent Zone	Above 50,000 ft > 15,240 m < 87 mmHg	Survival requires assisted PBA[a] or, above about 63,000 ft, a full pressure suit and delivery of 100% O_2 to supply at least 140 mmHg O_2	Pressurized cabin or pressure suit with 100% O_2

[a]PBA = positive pressure breathing for altitude.

2.1.3. Altitude

Altitude is measured in many different ways using different standards for different purposes (Table 2.1.3-1.).

Table 2.1.3-1. Type of Altitude Measurements

Type of Altitude	Definition
True Altitude	As measured with a tape measure from sea level to the aircraft
Mean Sea Level (MSL)	Average height of the surface of the sea
Pressure Altitude (PA)	Height read on an altimeter set to 29.92 inHg
Indicated Altitude	As read from a properly set altimeter
Above Ground Level (AGL)	Altitude determined by subtracting the elevation of the ground below the aircraft from the true altitude of the aircraft

True altitude is the standard to which other, more practical altitudes are compared. On low-altitude maps provided to USAF pilots, the height of physical features of the Earth, like mountains and airfields, is measured in feet above mean sea level (MSL). MSL is the average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings. With properly set, calibrated, and functioning altimeters, feet above MSL is the altitude viewed by the pilot on the

aircraft altimeter when flying below 18,000 ft. Since altimeter settings vary with atmospheric pressure variations, the MSL altitude will only be correct if the correct pressure is set in the Kollsman window of the altimeter (Fig. 2.1.3-1).

Pressure altitude (PA) is the height in the atmosphere at which a given value of standard pressure exists. With 29.92 inHg set in the Kollsman window of the altimeter (Fig. 2.1.3-1), pressure altitude is displayed in feet on the altimeters of USAF aircraft at or above 18,000 ft. This is the standard setting when aircraft are at or above 18,000 ft, where altitudes are referred to as flight levels, in hundreds of feet. For example, 20,000 ft is flight level 200 (FL200). Indicated altitude is the altitude read on an altimeter and will be MSL below 18,000 ft and, typically, pressure altitude above 18,000 ft with 29.92 set in the Kollsman window.

Pilots are naturally quite interested in the height of their aircraft above the ground. Above ground level (AGL) altitude is the altitude determined by subtracting the elevation, in feet, of the ground below the aircraft from the true altitude of the aircraft. This is the distance between the pilot and the ground (or an obstacle).

Although inHg is the standard for altimeter settings and is a pressure indication, it is not normally used in aviation for describing total atmospheric pressure at a given altitude. Elevation is typically measured in feet and pressure in psia or mmHg. In parts of the world, other measures are standard and listed in Appendices 1 & 2.

Since some controllers in the U.S. leave off the “2” of 29.92, confusion can arise when U.S. pilots “assume” that, for example, 998 means 29.98 inHg when given by an air traffic controller overseas. That overseas controller may mean 998 mb, which, if misinterpreted, could mean a difference of about 400 ft.

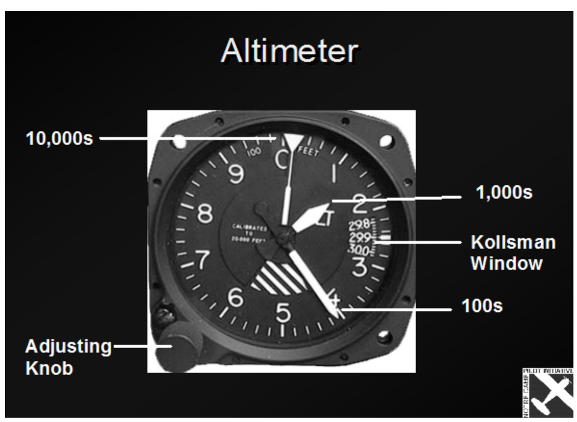

Figure 2.1.3-1. Altimeter and Aneroid

2.1.4. Air Density, Pressure, and Temperature

Atmospheric pressure decreases exponentially with increasing altitude, reaching 50% of sea level density and pressure at approximately 18,000 ft (5.49 km). This relationship is affected in any specific locale by deviations from standard temperature and pressure. Figure 2.1.4-1 graphically shows how atmospheric pressure is affected by altitude. The curve depicts how each 10,000-ft increase in altitude results in less change in pressure: 0-10,000 ft changing by 237 mmHg, 10,000-20,000 ft changing by

173 mmHg, and 40,000-50,000 ft changing by only 54 mmHg. This relationship explains why pressure effects from trapped gases are more noticeable in the lower altitude ranges. See section 2.2 (the Gas Laws) for implications of this pressure change.

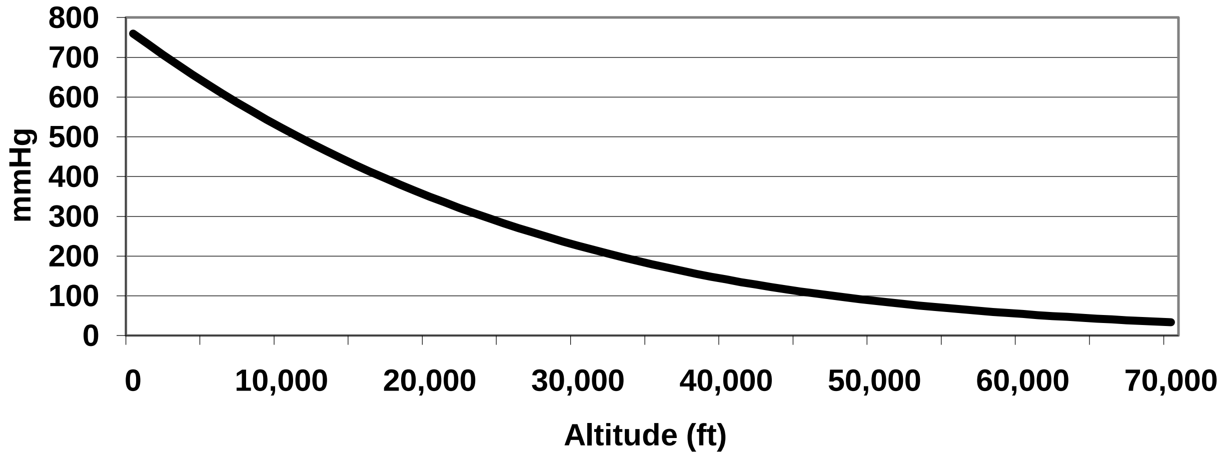

Figure 2.1.4-1. Atmospheric Pressure vs. Altitude

Flight altimeters are still based on air pressure, although modern methods based on radar and on the Global Positioning System are coming into use. During takeoff, landing, and low-level phases of flight, aircraft altimeters are routinely set to the field altimeter setting, i.e., the local barometric pressure at the airfield. Using this setting accounts for variations in local atmospheric pressure, which varies depending on meteorological conditions. Otherwise, the altimeter reading may vary significantly from true altitude at one of the most crucial phases of flight: flying close to the ground.

Temperature variations from the standard temperature of 15°C also produce errors that affect terrain clearance. For instance, an aircraft flying at 5,000 ft in –40°C (e.g., Alaska in the winter) would be more than 1,200 ft lower than the indicated altitude <u>after</u> correction for local barometric pressure. Local barometric pressure in the United States is based on inches of Hg. Setting the current local barometric pressure in the Kollsman window on the altimeter will result in a reading of 0 ft at sea level. As the local pressure varies, altimeters must be adjusted up or down to yield the correct field elevation on an aircraft altimeter at a designated point on that airfield. Above 18,000 ft (FL180, altitude in feet divided by 100), altimeters are routinely set to 29.92 inHg to provide adequate and standardized clearance for aircraft altitude separation.

2.1.5. Light and Sound

Diffusion of light in the lower atmosphere accounts for the blue color of the sky as viewed from Earth's surface, a phenomenon which significantly dissipates as low as about 50,000 ft where the blackness of space begins to become apparent. The speed of sound is 761 mph (340 m/s, 1,116 ft/s) at sea level. It travels slower, 660 mph (295 m/s) at 50,000 ft, where the temperature is about 75°C lower. The speed of sound is a function of the square root of the temperature in °K (°C + 273).

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Internet Resources; see Appendix 8
U.S. Standard Atmosphere, 1962 Washington, D.C.

Concepts

Atmospheric zones
Constituents of Earth's atmosphere
Physiological zone
Physiologically deficient zone
Standard atmospheric pressure

Vocabulary

Above ground level (AGL)
Indicated altitude
Lapse rate
Mean sea level (MSL)
Pressure altitude (PA)
Stratosphere
Tropopause
Troposphere

2.2. The Gas Laws

1662	Boyle published the finding that at a constant temperature, the volume of gas is inversely proportional to its pressure (Boyle, 1662).
1787	Jacques Alexandre César Charles discovered the relationship between the volume of gas and its temperature (Gay-Lussac, 1802).
1802	Joseph Louis Gay-Lussac published the Charles findings that the volume of fixed mass of gas is directly proportional to its absolute temperature (Gay-Lussac, 1802).
1803	William Henry published his findings that the amount of a gas in a solution varies directly with the partial pressure of that gas over the solution (Davis, 2008).
1805	John Dalton presented his observations that the total pressure of a mixture of gases is equal to the sum of the partial pressures of each gas in the mixture (Dalton, 1805).
1833	Thomas Graham described the diffusion of a gas as being inversely proportional to the square root of its molecular weight (Graham, 1833). In 1834 he received the Keith Prize from the Royal Society of Edinburgh for this work.

The Gas Laws describe physical properties of all gases, including our atmosphere, and provide a basis for understanding how exposure to reduced atmospheric pressure affects our function.

2.2.1. Pressure-Volume Law (Boyle's Law)

Robert Boyle (1627-1691) was an Anglo-Irish scientist noted for his work in physics and chemistry. In 1662, Boyle published the finding which states that at a constant temperature, the volume of gas is inversely proportional to its pressure. P_1 and V_1 are the initial pressure and volume, and P_2 and V_2 are the final pressure and volume.

$$P_1 \times V_1 = P_2 \times V_2 \; or \; \frac{P_1}{P_2} = \frac{V_2}{V_1}$$

Solving this equation for the volume of a gas in a distensible container, such as a balloon, quantitatively describes trapped gas expansion with reduced pressure. Solving this equation to find the volume of a liter of dry gas taken from sea level to 20,000 ft and 40,000 ft, assuming unrestricted expansion, would result in the increase in volume shown in Figure 2.2.1-1.

The problem becomes more complicated by the inclusion of water vapor in the lungs and other spaces in the body as described in section 3.4 on trapped gas.

$$\frac{760 \text{ mmHg } X 1 \text{ L}}{760 \text{ mmHg}} = 1.0 \text{ L at sea level}$$

$$\frac{760 \text{ mmHg } X 1 \text{ L}}{349 \text{ mmHg}} = 2.2 \text{ L at 20,000 ft}$$

$$\frac{760 \text{ mmHg } X 1 \text{ L}}{141 \text{ mmHg}} = 5.4 \text{ L at 40,000 ft}$$

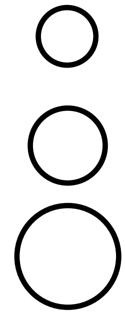

Figure 2.2.1-1. Volume Changes with Reduced Pressure

2.2.2. Volume -Temperature Law (Charles and Gay-Lussac's Law)

Jacques Alexandre César Charles (1746-1823) was a French inventor, scientist, mathematician, and balloonist. In 1783 he made the first balloon using hydrogen gas. Upon release it ascended to a height of nearly 3 km (2 mi). In 1787, he discovered the relationship between the volume of gas and temperature. Charles did not publish his findings, and Joseph Louis Gay-Lussac first published the findings in 1802, referencing Charles' work. Therefore, it is known variously as Gay-Lussac's Law or Charles's Law or Charles and Gay-Lussac's Law.

$$\frac{V_1}{V_2} = \frac{T_1}{T_2} \; or \; \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

The temperature must be expressed in Kelvin degrees, where $^oK = {}^oC + 273$. Absolute zero, -273^oC, is 0^oK.

Note that Boyle's pressure-volume law describes changes in volume with respect to pressure when temperature is held constant. Charles and Gay-Lussac's volume-temperature law describes how volume changes with temperature when pressure is held constant. Changes in all three parameters (volume, pressure, and temperature) are better described by the Ideal Gas Law, which includes the three parameters in one equation with other factors to improve accuracy.

Although Charles's volume-temperature law is very important from an engineering and chemistry standpoint, the temperature of the human body varies little, limiting the law's usefulness in physiology. It is of importance when considering the variation in pressure of compressed gases, such as oxygen tanks, when the temperature varies.

2.2.3. Ideal Gas Law

$$PV = nRT$$

where P = pressure, V = volume, T = temperature, n = number of moles, and R = universal gas constant = 8.3145 J/mol K.

The Ideal Gas Law includes the factors of volume, pressure, and temperature in a single equation, which explains the effects described by Boyle, Charles, and Gay-Lussac. Two added factors, n and R, are constants if the total quantity of gas is

constant. If the number of moles (quantity, number of molecules, of gas) is held constant, the effect of varying one factor can be seen on the other potential variables.

$$P = \frac{T}{V} \quad \text{or} \quad V = \frac{T}{P} \quad \text{or} \quad T = PV$$

In this case it can also be written so as to compare initial and final states, like Boyle's and Charles/Gay-Lussac's Laws:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

2.2.4. Law of Partial Pressures (Dalton's Law)

John Dalton (1766-1844) was an English chemist and physicist. In 1805, he described the total pressure of a mixture of gases as equal to the sum of the partial pressures of each gas in the mixture.

$$P_T = P_1 + P_2 + P_3 + \ldots P_n$$

Since the standard atmosphere at sea level is 760 mmHg, Dalton's Law indicates that the sum of the partial pressures of the gases that make up the standard atmosphere must equal 760 mmHg as shown in Table 2.1.2-1.

The pressure of each gas in a mixture of gases is independent of the pressure of the other gases in that mixture. Multiplying the percentage of a gas in the mixture times the total pressure of the mixture yields the partial pressure of that gas (Table 2.1.2-1).

The standard atmosphere does not include water vapor pressure, primarily due to its variation in the Earth's atmosphere between 0% and 100% relative humidity. That variation amounts to 0% to 6.2% of 760 mmHg, or 0 to 47 mmHg at body temperature, 37^{o}C. See section 3.4 on trapped gas about water vapor effects at high altitudes.

2.2.5. Law of Gaseous Diffusion (Graham's Law)

Experiments of Thomas Graham (1805-1869), a British chemist, showed that the diffusion of a gas is inversely proportional to the square root of its molecular weight. Thus, gases of lower molecular weight diffuse more rapidly than gases of higher molecular weight. Diffusion of a gas is also affected by the difference in concentration of the gas between two adjacent volumes. A larger difference in concentration produces greater diffusion.

$$\text{Diffusing Capacity} = \frac{1}{\sqrt{MW}}$$

Solubility also affects diffusion. A gas with greater solubility in its solvent, e.g., tissue or fluids, means more molecules of it will be available to diffuse as limited by the

other factors. Gaseous diffusion is fundamental to the physiologic processes of lung and cellular respiration. It further applies to the process of denitrogenation, removal of nitrogen from the body, by breathing 100% oxygen.

As an example of gaseous diffusion, Figure 2.2.5-1 shows what happens across the semi-permeable lung alveoli as a person begins to breathe 100% oxygen. Although this is a hypothetical figure, the principle of reaching equilibrium if diffusion were completed is shown. In the lung, equilibrium is likely not achieved due to the continuation of respiration. However, it can be seen that considerable N_2 diffuses from the capillary to the alveolus and considerable O_2 diffuses from the alveolus to the capillary. The solubility of CO_2 as a bicarbonate ion, HCO_3^- in capillary fluids, and O_2 uptake by hemoglobin in the capillaries complicate the values in this depiction, but the diffusion is in the direction shown.

BEFORE DIFFUSION

Capillary Blood		Alveolus Air
570 mmHg N_2	$\longrightarrow$	0 mmHg N_2
40 mmHg O_2	$\longleftarrow$	673 mmHg O_2
46 mmHg CO_2	$\longrightarrow$	40 mmHg CO_2
47 mmHg H_2O	$\longleftrightarrow$	47 mmHg H_2O

AFTER DIFFUSION

Capillary Blood		Alveolus Air
285 mmHg N_2	$\longleftrightarrow$	285 mmHg N_2 [increases]
357 mmHg O_2	$\longleftrightarrow$	357 mmHg O_2 [increases]
42 mmHg CO_2	$\longleftrightarrow$	42 mmHg CO_2 [increases]
47 mmHg H_2O	$\longleftrightarrow$	47 mmHg H_2O [no change]

Figure 2.2.5-1. Gaseous Diffusion of N_2, O_2, and CO_2 Between Alveoli and Capillaries After Beginning to Breathe 100% O_2

Water vapor, H_2O, is at equilibrium throughout the process of respiration at the alveolar level shown in Figure 2.2.5-1. Hence, there is no change in the 47-mmHg partial pressure of water vapor in the alveoli at body temperature. This constant partial pressure of water vapor at body temperature becomes very important at very high altitudes because it represents a higher percentage of the gases present. At 63,000 ft, Armstrong's Line, the total pressure is 47 mmHg. See section 3.4.1 for the implications of exposure to that altitude without a pressure suit.

2.2.6. Law of Dissolved Gas Partial Pressure (Henry's Law)

William Henry (1775-1836) was an English chemist who, in 1803, published his findings that the amount of a gas in a solution varies directly with the partial pressure of that gas in contact with the solution. This relationship explains why dissolved nitrogen transitions to a gas phase in blood and tissues during decompressions sufficient to result in supersaturation. The resulting bubbles of nitrogen with minor amounts of oxygen, carbon dioxide, and water vapor can cause decompression sickness.

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Dalton J. Experimental Enquiry into the Proportion of the Several Gases or Elastic Fluids, Constituting the Atmosphere. Memoirs of the Literary and Philosophical Society of Manchester 1805; 1:244-58.
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U.S. Standard Atmosphere, 1962 Washington, D.C.

Recommended Readings

Davis JR, Johnson R, Stepanek J, Fogarty JA, Eds. Fundamentals of Aerospace Medicine. 4th Ed. Lippincott Williams & Wilkins. 2008.
Ernsting J. Prevention of hypoxia – Acceptable Compromises, Aviat Space Environ Med 1978; 49:495-502.

Concepts

Ideal Gas Law
Law of dissolved gas partial pressure
Law of gaseous diffusion
Law of partial pressures
Pressure-volume law
Volume-temperature law

Vocabulary

Diffusion
$P_1 \times V_1 =$
$P_T =$
$PV = nRT$
$V_1/V_2 =$

3. ATMOSPHERIC ENVIRONMENTAL EFFECTS

3.1. Alveolar Gas Equations

James T. Webb, Ph.D.

As described in the previous section, the percentage of oxygen is a consistent 21% of the total atmosphere throughout the altitudes in which aircraft operate. Accordingly, as the total pressure decreases with altitude, 21% of the shrinking total is less. Thus, as described by Dalton's Law, the partial pressure of oxygen decreases with altitude.

The tables in Appendix 1 (altitude of exposure vs. alveolar partial pressure of oxygen) are based on the U.S. Standard Atmosphere (1962) geometric altitude. The following nomenclature is used throughout this document to describe the relationships between gases of importance to human physiology.

- PB: Barometric pressure in mmHg
- FIO_2: The fraction of the total inspired air which is oxygen; the fraction of oxygen in atmospheric air is 21% (0.21) 21%
- PTO_2: Partial pressure of oxygen in the trachea
- PAO_2: Partial pressure of oxygen in the alveoli
- $PACO_2$: Partial pressure of carbon dioxide in the alveoli, 40 mmHg at sea level, but decreases during exposure to lower total pressure due to hyperventilation caused by the lower PAO_2
- PAH_2O: Partial pressure of water vapor *at* body temperature, a constant 47 mmHg
- R: The respiratory quotient (exchange ratio; R or RQ; CO_2 elimination/O_2 consumption)

R increases with increasing altitude due to hypoxia-induced hyperventilation that increases CO_2 elimination, the same phenomenon observed during strenuous exercise with increased ventilation rate or during hyperventilation. The R, normally about 0.83 at sea level, is also affected by diet due to the varying ratio of carbon to oxygen in various foods. Fat has a relatively high ratio of carbon to oxygen and requires more respiratory oxygen when metabolized by the body, thus lowering the R to 0.70. Metabolism of carbohydrates, which contain much more oxygen, yields an R of 1.0 and protein metabolism yields an R of 0.80.

$$PTO_2 = (PB - PAH_2O) \text{ X } FIO_2 \text{ atmosphere}$$

At sea level pressure this becomes

$$PTO_2 = (760 - 47) \text{ X } 0.21 = 149.7 \text{ mmHg}$$

$$PAO_2 = PTO_2 - PACO_2 \text{ X } (FIO_2 + (1 - FIO_2) \text{ X } R^{-1})$$

At sea level pressure, this equation for alveolar oxygen partial pressure becomes $PAO_2 = 149.7 - 40 \text{ X } (0.21 + (1 - 0.21) \text{ X } 0.85^{-1}) = 149.7 - 45.6 = 104.1$ mmHg. Plotting the

PAO_2 values versus altitude breathing air or 100% oxygen using the equation above yields curves that depict the varying PAO_2 over the range of most USAF missions (Figs. 3.1.1-1 and 3.1.1-2).

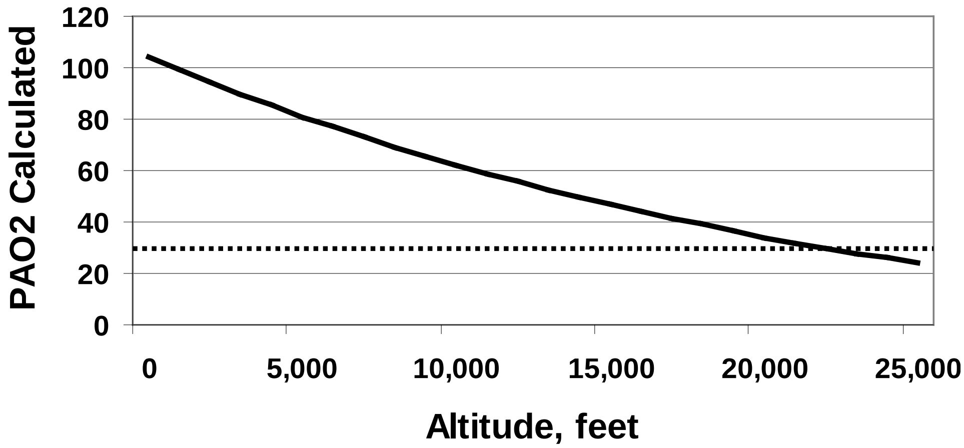

Figure 3.1.1-1. Calculated PAO_2 in mmHg as a Function of Altitude and Breathing Air (from Appendix 1a)

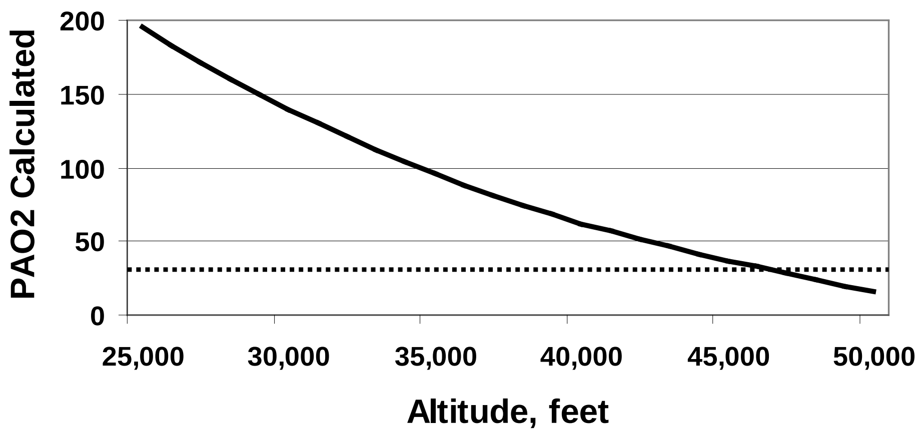

Figure 3.1.1-2. Calculated PAO_2 in mmHg as a Function of Altitude and Breathing 100% Oxygen (from Appendix 1b)

Note for Figures 3.1.1-1 and 3.1.1-2: The dashed lines at 30 mmHg represent the approximate level of alveolar oxygen needed to maintain consciousness (Ernsting et al., 1999). The line in Figure 3.1.1-2 is based on data in Appendix 1b as adjusted to reflect no PBA (positive pressure breathing for altitude; see Section 4, Personal Equipment Effects).

The minimum fraction of inspired oxygen (FIO_{2NP}) delivered by a USAF narrow panel regulator (CRU 73/P) is a function of altitude in the cockpit/cabin. The regulator adds 100% oxygen to atmospheric air, diluting the air with oxygen. To calculate the FIO_{2NP} delivered at a specific altitude (dotted line in Figure 3.1.1-3), the following formula can be used:

$$FIO_{2NP} = \%\ O_2 \text{ added} + 0.21 \text{ X } (100 - \%\ O_2 \text{ added})$$

At 25,000 ft in Figure 3.1.1-3, the % O_2 added is about 47%, thus

$$FIO_{2NP} = 47 + 0.21 \text{ X } (100 - 47) = 58\% \text{ at 25,000 ft}$$

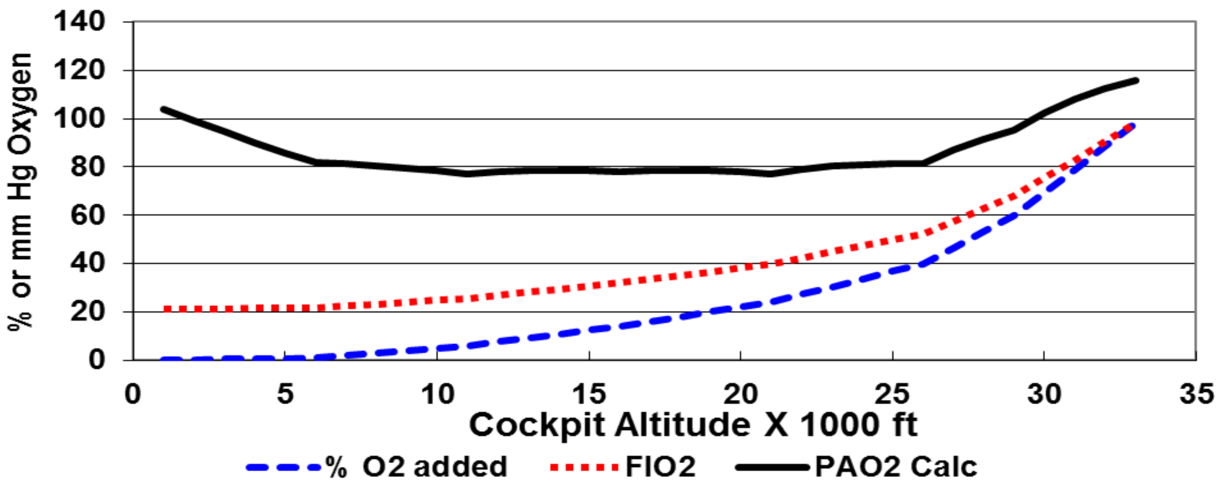

Figure 3.1.1-3. Minimum Level of Oxygen Delivered by USAF Narrow Panel Regulator CRU 73/P (Data from MIL-R-83178)

References

Ernsting J. Prevention of hypoxia – Acceptable Compromises, Aviat Space Environ Med 1978; 49:495-502.

MIL-R-83178 USAF

Recommended Reading

Davis JR, Johnson R, Stepanek J, Fogarty JA, Eds. Fundamentals of Aerospace Medicine. 4th Ed. Lippincott Williams & Wilkins. 2008.

Concepts

Alveolar gas equation

$PTO_2 = (PB - PAH_2O) \text{ X } FIO_2$ atmosphere

$PAO_2 = PTO_2 - PACO_2 \text{ X } (FIO_2 + (1- FIO_2) \text{ X } R^{-1})$

PBA

Vocabulary

PB

FIO_2

PTO_2

PAO_2

$PACO_2$

PAH_2O

R

3.2. Hypoxia

James T. Webb, Ph.D.

3.2.1. Definition and Causes

Hypoxia means “reduced oxygen” or “not enough oxygen.” A complete lack of oxygen is called anoxia. Although any tissue will die if deprived of oxygen long enough, the brain is particularly vulnerable to oxygen deprivation. Any reduction in mental function while flying can result in life-threatening errors. Hypoxia can be caused by several factors including an insufficient supply of oxygen, inadequate transportation of oxygen, or the inability of the body tissues to use oxygen. Table 3.2.1-1, Causes of Hypoxia, shows the relationship between phases of respiration, problems encountered, and the common term for the type of hypoxia produced.

3.2.2. Hypemic Hypoxia

Hypemic hypoxia occurs when the blood is not able to take up and transport a sufficient amount of oxygen to the cells in the body. Hypemic means “not enough blood.” This type of hypoxia is a result of oxygen deficiency in the blood, rather than a lack of inhaled oxygen, and can be caused by a variety of factors. One example is decreased blood volume due to severe bleeding or blood donation. Blood can take several weeks to return to normal following a donation. Although the effects of the blood loss are slight at ground level, there are risks when flying during this time. Certain blood diseases, such as anemia, can also cause hypemic hypoxia. The most common cause of hypemic hypoxia is due to the inability of hemoglobin, the actual blood molecule that transports oxygen, to bind oxygen molecules, such as occurs during carbon monoxide poisoning. Carbon monoxide binds to hemoglobin 200 times more effectively than does oxygen. Treatment with 100% oxygen is an effective way of getting some oxygen to the tissues and to speed “wash out” of the carbon monoxide. Hyperbaric oxygen treatment supplies oxygen in a pressurized chamber and is capable of providing oxygen at many times the normal amount in air. This is much more effective than 100% oxygen at sea level pressure.

3.2.3. Stagnant Hypoxia

Stagnant means “not flowing,” and stagnant hypoxia results when the oxygen-rich blood in the lungs isn’t moving, for one reason or another, to the tissues that need it. An arm or leg going to sleep because the blood flow has accidentally been shut off is one form of stagnant hypoxia. This kind of hypoxia can also result from shock, the heart failing to pump blood effectively, or a constricted artery. During flight, stagnant hypoxia can occur when pulling excessive $+G_z$ as discussed in section 7.1, Physiologic Effects of Acceleration, mission-imposed stressors section. Stagnant hypoxia is also called ischemic or circulatory hypoxia.

Table 3.2.1-1. Causes of Hypoxia

Phase of Respiration	General Problem	Examples of Causes (Specific Problems)	Common Term for Type of Hypoxia
Ventilation	Reduction in PAO_2	1. Breathing air at reduced barometric pressures 2. Strangulation, respiratory arrest, laryngospasm 3. Severe asthma 4. Breath-holding 5. Hypoventilation 6. Breathing gas mixtures with insufficient O_2 pressure or % a. Environments with reduced O_2 available; smoke and fumes b. Malfunctioning oxygen equipment at altitude	Hypoxic hypoxia
	Reduction in gas exchange area	1. Pneumonia 2. Drowning 3. Atelectasis 4. Emphysema/COPD (chronic obstructive pulmonary disease) 5. Pneumothorax 6. Pulmonary embolism 7. Congenital heart defects 8. Physiological shunting	Hypoxic hypoxia
Diffusion	Diffusion barriers	1. Hyaline membrane disease 2. Pneumonia 3. Drowning 4. Reduction of alveolar function by smoke/fumes	Hypoxic hypoxia
Transportation	Reduction in oxygen-carrying capacity	1. Anemia 2. Hemorrhage, blood donation or loss 3. Hemoglobin abnormalities 4. Drugs and chemicals (smoke and fumes; sulfanilamides, nitrites, cyanide, carbon monoxide)	Hypemic hypoxia
	Reduction in systemic blood flow	1. Heart failure 2. Shock 3. Continuous positive pressure breathing 4. Acceleration (G forces) 5. Pulmonary embolism	Stagnant hypoxia
	Reduction in regional or local blood flow	1. Exposure to extremes of environmental temperatures 2. Postural changes (esp. following prolonged sitting or bed rest) 3. Tourniquets (including restrictive clothing, straps, etc.) 4. Hyperventilation 5. Embolism by clots or gas bubbles 6. Cerebral vascular accidents	Stagnant hypoxia
Utilization	Metabolic poisoning or dysfunction	1. Respiratory, enzyme poisoning or degradation 2. CO; smoke and fumes 3. Cyanide 4. Alcohol	Histotoxic hypoxia

Source: AFP 160-5, Table 4-1.

3.2.4. Histotoxic Hypoxia

The inability of the cells to effectively use oxygen is defined as histotoxic hypoxia. "Histo" refers to tissues or cells, and "toxic" means poison. In this case, plenty of oxygen is being transported to the cells that need it, but they are unable to make use of it. This impairment of cellular respiration can be caused by alcohol, narcotics, carbon monoxide, and poisons such as cyanide. Research has shown that drinking 1 oz of alcohol can equate to about an additional 2,000 ft of physiological altitude.

3.2.5. Hypoxic Hypoxia (Altitude Hypoxia)

Hypoxic hypoxia is a result of insufficient oxygen available to the lungs, or low PAO_2. A blocked airway or drowning are obvious examples of how the lungs can be deprived of oxygen, but the reduction in partial pressure of oxygen at high altitude is an appropriate example for aircrew. Although the percentage of oxygen in the atmosphere is constant, its partial pressure decreases proportionately as atmospheric pressure decreases. As the airplane ascends during flight, the percentage of each gas in the atmosphere remains the same, but there are fewer molecules of each, including oxygen, available to diffuse through the alveolar membranes of the lungs. This decrease of oxygen molecules can lead to hypoxic hypoxia, also called altitude hypoxia. Appendix 1 shows the alveolar oxygen levels resulting from exposure to altitude breathing air up to 45,000 ft (Appendix 1a), breathing 100% oxygen from 25,000 to 50,000 ft with positive pressure breathing for altitude (Appendix 1b), and breathing 100% oxygen from 50,000 to 70,000 ft with PBA (Appendix 1c). Pressure breathing requires the crewmember to "reverse breathe," since the pressure supplied inflates the lungs with no effort from the crewmember during inhalation. Exhalation during PBA is accomplished by forcing air out instead of relaxing and can be very tiring. With training and experience, an individual can pressure breathe "against" a 50-mmHg pressure for a short time, but even a 30-mmHg gradient will cause fatigue, and higher levels require assisted PBA with a counterpressure jerkin that helps to restrain chest expansion and reduce the effort involved during exhalation (Ernsting et al., 1999).

The terms "effective performance time" (EPT) and "time of useful consciousness" (TUC) describe the maximum time the crewmember has to make rational, life-saving decisions and carry them out at a given altitude without supplemental oxygen. It is important to note that EPT is a very rough guide, affected by many factors other than altitude. It cannot be used to predict how long an individual will be "useful" in any given situation. The variability in EPT means that observers must be diligent during chamber training flights to ensure that once EPT has been reached for any participant, proper procedures are initiated. With timely and adequate oxygen supplied to crewmembers who reached their EPT prior to initiating recovery procedures themselves, unconsciousness and potential brain damage can be avoided.

3.2.6. Environmental Factors that Affect Severity of Hypoxia

The partial pressure of oxygen available is related to altitude and breathing gas as shown in Figures 3.1.1-1, 3.1.1-2, and 3.1.1-3 and in Appendix 1. Between 30,000 and 40,000 ft, automatic pressure-demand oxygen regulators are designed to deliver 100% oxygen with a slight "safety" pressure, 3 to 4 mmHg above ambient, to prevent

inboard mask leakage. Use of 100% oxygen at these altitudes was recognized in 1944 as providing for "maximum efficiency" (Fig. 3.2.6-1).

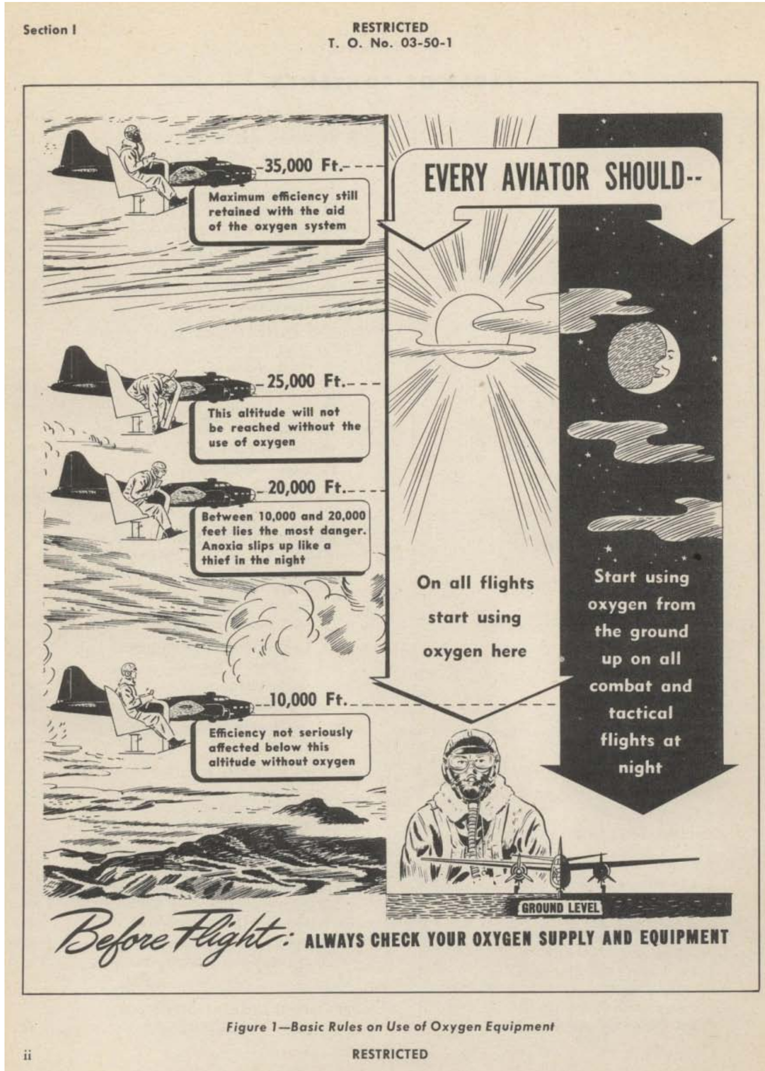

Figure 3.2.6-1. "Use of Oxygen and Oxygen Equipment" T.O. No. 03-50-1 (1944)

At altitudes above 40,000 ft, the positive pressure delivered to the mask increases with increasing altitude, as shown in Appendix 1b and 1c. This additional pressure increases the total pressure of 100% oxygen delivered to the mask and is called positive pressure breathing for altitude.

PBA may include the addition of a counterpressure vest to provide external pressure on the thorax during pressure breathing.

Rate of ascent/rapid decompression is a factor, with greater severity if the decompression is rapid, meaning between 2 and 15 s (Davis et al., 2008). A rapid decompression compounds the effect of hypoxia by potentially creating a diffusion gradient, which drives oxygen from blood back into the lungs. A rapid decompression from a cabin altitude of about 18,700 ft to an ambient altitude of 45,000 ft with a 5-psid

pressurization system (7.15 psia to 2.15 psia) while breathing 37% oxygen (minimum delivered by the USAF narrow panel regulators, Fig. 2.2.1-3) provides such a situation. The cruise PAO_2 before the rapid decompression would be approximately 79 mmHg, equivalent to breathing air at about 5,500 ft. This is not a problem for a relatively inactive crewmember. However, the first few breaths of the 37% oxygen in the mask and hose after a rapid decompression to 45,000 ft would yield a PAO_2 far below 30 mmHg. This is insufficient to maintain consciousness if maintained for more than a few seconds (Ernsting, 1978). Several breaths may be required for the residual mixture in the supply line to be replaced with the higher concentration of oxygen being supplied at the regulator. Indeed, the blood reaching tissues shortly after such a rapid decompression would have less oxygen than the tissues, causing removal of oxygen from the tissues. For these reasons, the EPT following rapid decompression to altitude while breathing air is less than shown in Appendix 1a. Appendix 1a is based on a decompression typical of aircraft climb rate, 1,000 to 10,000 ft/min. It is likely that respiration rate would increase significantly immediately following a rapid decompression due to the stress of an emergency. This would hasten delivery of 100% oxygen to the crewmember and may prevent unconsciousness for those wearing masks at the time of decompression. Those who quickly don masks set to deliver 100% oxygen will have the same reversal of the usual direction of diffusion until they fill their lungs with oxygen. It is critical in training to stress that each individual must take care of himself or herself first!

A rapid decompression to 60,000 ft, even if breathing 100% oxygen prior to the decompression and with 60 mmHg of PBA after the decompression, would yield a PAO_2 less than 55 mmHg, equivalent to breathing air at about 13,000 ft (Appendix 1a and 1c). Although 70 mmHg of PBA would increase the PAO_2 significantly at 60,000 ft, assisted positive pressure breathing (PPB) (using a chest counterpressure device) would be necessary to avoid extreme difficulty in regulating breathing.

A rapid decompression, 2-15 s (section 4.1.7), can present additional dangers beyond hypoxia. A rapid decompression may cause lung overinflation with more than 80 mmHg of transthoracic pressure. A breath-hold during a rapid decompression could exacerbate the condition, leading to a pulmonary air embolism: transfer of gas from the lung to the circulatory system (not ebullism; see Glossary and section 2.2.5). Differential transthoracic pressure of up to 80 mmHg (Luft & Bancroft, 1956) has been tolerated without injury and without assisted PPB including a counterpressure jerkin. Air embolism in the arterial system may lead to several symptoms resembling acute neurologic decompression sickness (DCS). Onset of symptoms from an air embolism is much faster than from DCS, and treatment by immediate descent while breathing 100% oxygen should be followed by hyperbaric oxygen (HBO) treatment as necessary.

Slow decompression has its own characteristic risk; it is insidious. There is no loud noise or fogging of the air to draw attention. As pressure is slowly lost, signs and symptoms develop slowly. It is possible to suffer the debilitating effects of hypoxia without recognizing their presence in the absence of cabin pressure warning systems. This has dangerous and sometimes fatal consequences.

Duration at altitude is a factor because remaining at altitudes between about 20,000 and 30,000 ft after a fast decompression (less than about 3 min) increases the chance of loss of consciousness due to depletion of tissue oxygen reserves. Also, physiologic compensatory mechanisms are limited. At these altitudes, a timely decision to descend should prevent altitude-induced loss of consciousness if other remedies are insufficient to provide adequate oxygenation.

A higher ambient temperature and/or an increase in humidity correspond to decreased air density and, therefore, a small reduction of the partial pressure of oxygen. Higher temperature increases body metabolism, which increases oxygen demand. Although both effects are small, their combined effect may increase the severity of hypoxia.

There is considerable variation in individual tolerance to hypoxia. Factors that are known to affect hypoxia tolerance are the level of physical fitness and several other factors that affect the ability to utilize available oxygen. Good physical fitness offers some protection from hypoxia, particularly if physical activity is involved in the hypoxic episode. The increased perfusion and ventilation capabilities of athletic-level fitness provide more pathways for oxygen delivery and utilization. Note however, that if alveolar PO_2 drops below pulmonary capillary PO_2 as described in the rapid decompression discussion above, there are more pathways for oxygen to leave the blood, too. Physical fitness provides no immunity to hypoxia.

Since physical activity involves elevated oxygen consumption, a lower oxygen partial pressure will adversely affect maximal exercise capability. Increased respiration rate induced by peripheral oxygen chemoreceptors will partially reverse this effect, in part by reducing the partial pressure of carbon dioxide in the alveoli, allowing a little more oxygen to be present.

Acclimatization to altitude is a multifaceted process involving increased ventilation, a shifting of the oxygen-hemoglobin dissociation curve (section 1.2, Respiration) to the right to facilitate oxygen delivery at the tissue level, increased red blood cell count (higher erythrocyte count and hematocrit), increased vascularization (more capillaries per unit volume of tissue), and an increase in muscle myoglobin concentration. Some improvement in function can be observed in a few days due to the first two items, but the remaining changes take months to reach steady state. However, even acclimatization of several weeks is insufficient to compensate for the oxygen requirements of mild exercise above about 18,000 ft (Hb saturation about 72%; Davis et al., 2008).

Metabolic rate is affected by emotional state. A highly agitated, excited, angry, or scared individual will require more oxygen for optimal function, and mild hypoxia could become worse under those emotional conditions. Hyperventilation can also further complicate the physiological reaction.

Medication and drugs can affect metabolic rate, oxygen utilization, respiration rate, and other factors that bear on susceptibility to hypoxia. Alcohol has long been recognized as having a synergistic effect with hypoxia. Smoking reduces available hemoglobin by 4% to 7% because carbon monoxide in cigarette smoke combines with hemoglobin. Prescription medications may also interfere with cellular respiration. These effects are negligible at low altitude but reduce the reserves of the system in hypoxic environments. For this reason, aircrew must have all medications, whether prescription or over-the-counter, approved by a flight surgeon.

3.2.7. Effects of Hypoxia on Vision

The subtle effects of lack of adequate oxygen on vision are readily apparent during training in a darkened chamber at 18,000 ft once supplemental oxygen is supplied. It is difficult to detect these negative effects without such a demonstration, but at least some negative effects have been documented at or above 10,000 ft (Balldin et al., 2007). This was especially true when using any night vision devices (NVDs).

Increasing the rod and cone threshold was described as the main effect on hypoxic hypoxia (Miller & Tredici, 1992). Scotopic vision (vision during reduced illumination; see Section 1.4.6) at 10,000 ft was reported to be decreased by 20% and 35% at 13,000 ft without supplemental oxygen.

3.2.8. Recognition

Experiencing hypoxia with prior knowledge that it will happen allows trainees to recognize their individual symptoms and practice self-treatment to limit the severity of symptoms and prevent loss of consciousness. Since individual symptoms tend to be consistent on subsequent hypoxic episodes (Cable, 2003; Files et al., 2005), awareness can cue a crewmember to the possibility of hypoxia so the crew can take the appropriate emergency procedural actions (see Checklists in Appendix 5). Altitude chamber training provides an opportunity for crewmembers to recognize their own symptoms and practice corrective measures. The chamber training also allows crewmembers to observe objective signs of hypoxia in other trainees, further reinforcing their understanding of the dangers of hypoxia while in safe, controlled conditions.

3.2.9. Smoke and Fumes

Smoke and fumes in an enclosed space such as a cockpit or aircraft cabin can induce hypoxia via interference with any of the phases of respiration (Table 3.2.1-1).

- Ventilation – by displacing the oxygen
- Diffusion – by interfering with alveolar function
- Transportation – by interruption of hemoglobin's capability to transport oxygen (CO poisoning)
- Utilization – CO poisoning, etc.

Aircraft checklists for smoke and fumes typically direct crewmembers to select 100% oxygen (ON) and then take steps to isolate the cause and take appropriate action. Oxygen systems that deliver less than 100% oxygen do so by diluting with ambient (cabin) air, which will be contaminated in a smoke and fumes environment. For aircraft in which crewmembers wear an oxygen mask throughout flight, the same procedure would apply but may emphasize checking the oxygen delivery system to ensure it is not the source of the problem.

3.2.10. Stages and Symptoms of Hypoxia

The stages of hypoxia are categorized by the level of symptoms experienced as a result of reducing arterial oxygen saturation as shown in Table 3.2.10-1. The Indifferent Stage is characterized by only low levels of hypoxia with some increase in respiration rate, possibly not noticed by a person at rest. The Compensatory Stage name appears to indicate humans can compensate for the reduction in percent of saturation of arterial blood with oxygen. However, the degree of hypoxia is sufficient to preclude adequate physiologic and cognitive function despite increases in breathing depth and rate, which provide some compensation. Hence, persons in control of aircraft are required to breathe supplemental oxygen at altitudes above 10,000 ft.

Table 3.2.10-1. Stages of Hypoxia

Stage	Altitude (ft)		Arterial O_2
	Breathing Air	Breathing 100% O_2	Saturation (%)
Indifferent	0 to 10,000	34,000 to 39,000	95 to 90
Compensatory	10,000 to 15,000	39,000 to 42,500	90 to 80
Disturbance	15,000 to 20,000	42,500 to 44,800	80 to 70
Critical	20,000 to 23,000	44,800 to 45,500	70 to 60

In the Disturbance Stage, physiologic compensatory responses such as increased respiration and heart rate are not adequate to allow adequate function. The Critical Stage indicates a critical reduction in functional capability leading to loss of useful consciousness (see Appendix 1a for EPT while breathing air).

High altitude flying can place an aircrew member in danger of becoming hypoxic if insufficient oxygen is delivered to compensate for the reduced partial pressure of oxygen in the cabin/cockpit. Without sufficient oxygen, the brain and other vital organs become impaired. During the onset of hypoxia, an early symptom may be euphoria (Table 3.2.10-2), a carefree feeling, which could affect recognition and judgment, delaying a check of the oxygen system. Increased depth of breathing is usually an early sign or symptom, possibly accompanied by oxygen want, or air hunger.

Table 3.2.10-2. Symptoms of Hypoxia

Objective (Signs, Observable in others)	Subjective (Symptoms, Self-Observed)
Cyanosis (blue fingernails and lips)[a]	Air hunger or oxygen want
Decreased reaction time	Apprehension (worried or nervous)
Euphoria (unusually happy) [a] or belligerence	Dizziness
Impaired judgment	Fatigue
Increased respiration (increased depth/rate of breathing)[a]	Headache
Mental confusion[a]	Hot and cold flashes
Muscle incoordination[a]	Lightheaded or dizzy sensation
Unconsciousness	Nausea
	Numbness
	Tingling in fingers and toes
	Visual impairment (blurred/tunnel vision, dimming of light or color, etc.)

[a]Could also be self-observed.

With increased oxygen starvation, the extremities become less responsive and flying becomes less coordinated. The symptoms of hypoxia vary with the individual, but common symptoms include objective signs and subjective symptoms and some manifestations that may fall in both categories.

As hypoxia worsens, the field of vision begins to narrow, and instrument interpretation can become difficult. Even with all these symptoms, the effects of hypoxia can cause a crewmember to have a false sense of security and be deceived into believing that everything is normal. The treatment for hypoxia is more oxygen, either by flying at lower altitudes and/or use of supplemental oxygen.

Everyone is susceptible to the effects of hypoxia, regardless of physical endurance or acclimatization. When flying at high altitudes, it is paramount that oxygen be used to avoid the effects of hypoxia. As altitude increases above 10,000 ft, the

symptoms of hypoxia increase in severity, and the EPT rapidly decreases above 20,000 ft (Fig. 3.2.10-3 and Appendix 1a).

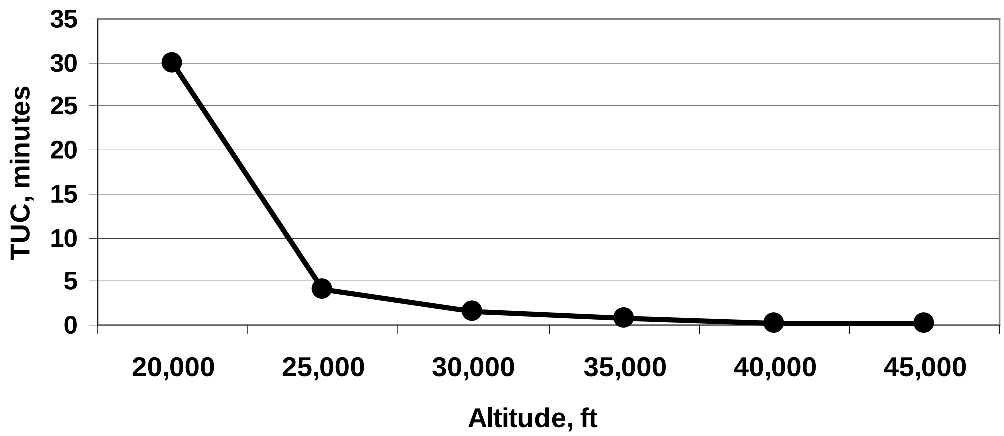

Figure 3.2.10-3. EPT Breathing Air vs. Altitude

At 10,000 ft, the PAO_2 while breathing air is about 62 mmHg, which yields an arterial oxygen saturation of about 87%. This is in the range of oxygen saturation with deleterious effects on performance (Crow & Kelman, 1971; Denison et al., 1966). While EPT provides a rough guide, the assumption should never be made that at a given altitude a given individual's EPT will match the "book value." Too many factors contribute, and particularly in a slow decompression, the onset of hypoxia may go unnoticed for many minutes. In this case, much of the EPT is already gone by the time recognition makes corrective action possible. Since symptoms of hypoxia can be different for each individual, the ability to recognize hypoxia can be improved by experiencing and witnessing the effects of it during an altitude chamber flight or with a reduced oxygen breathing device, which uses carefully calibrated mixed gas to provide a reduced partial pressure of oxygen.

3.2.11. Hyperventilation

Hyperventilation is an increase in ventilation beyond that driven by blood carbon dioxide levels, the normal driver for rate and depth of breathing. It can be caused by emotional stress, fright, or pain. Hypoxia (caused by altitude or by extreme physical exertion) can cause hyperventilation, as can the use of oxygen equipment, especially if that equipment supplies breathing gas with added pressure. The increase in breathing rate and depth causes the carbon dioxide level in the blood to be reduced below normal. The resulting hypocapnia, reduced blood carbon dioxide, can result in unconsciousness, at which point the respiratory system will regain control of breathing.

Hyperventilation is not “too much air” or “too much oxygen.” Signs and symptoms of hyperventilation are:

Headache	Lightheaded or dizzy sensation
Decreased reaction time	Tingling in fingers and toes
Impaired judgment	Numbness
Euphoria	Pale, clammy appearance
Visual impairment	Muscle spasms
Drowsiness	Tetany

Many symptoms of hypoxia and hyperventilation are identical or similar. This can confuse diagnosis and potentially delay treatment. Some differences in the manifestation of hypoxia and hyperventilation symptoms are shown in Table 3.2.11-1, but in an emergency or uncertain environment, time should not be wasted attempting to distinguish between them.

Table 3.2.11-1. Differences Between Symptoms of Hypoxic Hypoxia and Hyperventilation[a]

Signs and Symptoms	Hypoxic (Altitude) Hypoxia	Hyperventilation[b]
Onset of symptoms	Rapid (altitude dependent)	Gradual
Muscle activity	Flaccid, limp	Spasm
Appearance	Cyanosis	Pale, clammy
Tetany	Absent	Present

[a]From DeHart (1985).
[b]See discussion of hyperventilation in section 1.2.10.

Although the usual causes and mechanisms of action are different, because hypoxia is a deadly condition while hyperventilation is self-limiting, treating the two can and should be achieved by following one procedure, shown below in 3.2.12 and in Appendix 4. However, if hyperventilation occurs where there is reasonable assurance hypoxia is not involved, e.g., at sea level, control of rate and depth of breathing will treat the condition. In addition to slowing the breathing rate, breathing into a paper bag or talking aloud helps to overcome hyperventilation. Recovery is usually rapid once the breathing rate is returned to normal.

3.2.12. Treatment of Hypoxia and Hyperventilation

At the most elementary level, the treatment of hypoxia involves providing oxygen. Following the **BOLD FACE** procedures provides oxygen and restores normal breathing rate and depth, thus treating both hypoxia and hyperventilation simultaneously and without delay. Two procedures are shown, particular to the type of oxygen regulator used.

1. **CRU-73/A and CRU-68/A Narrow Panel Regulators**: All 3 switches up:
   SUPPLY - ON; OXYGEN - 100% OXYGEN; EMERGENCY
   CRU-93/A and CRU-98/A Narrow Panel Regulators: All 3 switches up:
   SUPPLY - ON/PBG; OXYGEN - 100% OXYGEN; EMERGENCY
   F-22 BRAG Valve Panel
   OBOGS - ON; SUPPLY - Normal; Mixture - Max
   This ensures that 100% oxygen will be available to the crewmember's supply line within seconds, assuming the system is operational and properly preflighted by the crewmember.
2. MASK – ON. It is natural to think that this step should be first. However, for those who do not regularly wear masks, especially if they do not have the quick-don type of emergency delivery, critical time is lost putting on the mask without any oxygen flowing through it. By taking the simple action of gangloading the regulator, oxygen will already be flowing and available for breathing during the mask fit and attachment.
3. Check regulator and connections.
   Steps 2 & 3 ensure that 100% oxygen will be available to the crewmember. This step detects an unconnected hose or malfunctioning regulator or mistakenly gangloading one regulator and hooking up to another. (See rate of ascent/rapid decompression in section 3.2.6.)
4. Control rate and depth of breathing.
   This step is needed to prevent hyperventilation, especially with a pressurized source of breathing gas, and to eliminate the cause of preexisting hyperventilation (cure).
5. Notify aircraft commander, lead, or other flight members.
   Depending on the effectiveness of the previous steps and the speed of the decompression, notifying someone else is important in case the hypoxia gets worse and because the cause may have gone unnoticed by others, such as failure to pressurize on ascent or smoke and fumes.
6. Descend to below 10,000 ft MSL.

Hypoxia training in an altitude chamber or with a reduced-oxygen breathing device can teach an individual how to recognize signs and symptoms and initiate well-established recovery steps. Providing aid to someone who is unconscious under likely hypoxic conditions dictates a similar course of action beginning with administration of supplemental oxygen. Although providing oxygen to an extremely hypoxic individual is essential for recovery, symptoms may, at first, seem to get worse, with the individual feeling dizzy and nauseated, and even trying to remove an oxygen mask. In severe cases, breathing may cease entirely for many seconds after a deep breath of oxygen. These symptoms are called oxygen paradox and usually pass quickly. The cause of **oxygen paradox** is believed to be hypocapnia resulting from hyperventilation during hypoxia. As a result, plasma carbon dioxide is insufficient to drive the respiratory reflex. During hypoxia, oxygen drives respiration. The first breath of oxygen eliminates this drive, and many seconds pass before carbon dioxide builds up enough to again drive respiration. Oxygen administration also affects capillary flow control and causes transient reductions in blood pressure, leading to dizziness and nausea.

3.2.13. Prevention of Hypoxia

Since the root cause of hypoxia is insufficient oxygen at some point in respiration, whether ventilation, diffusion, transportation, or utilization, prevention involves ensuring all phases of respiration are functioning adequately. Hypoxic hypoxia is the most common form of hypoxia in aviation and is commonly avoided by adequate cabin/cockpit pressurization. Aircraft that do not have adequate pressurization for hypoxia prevention provide oxygen systems which, if properly supplied, maintained, checked, and operated, ensure that crewmembers have adequate oxygen at the alveolar level. Exceptions would be operation of aircraft at such high altitudes that the aircraft systems' capabilities and/or aircrew personal equipment are overextended. Such results could occur if some newer generation fighters are allowed to be operated above 50,000 ft without personal protective equipment and aircrew training designed for this environment. New unpressurized tilt-rotor aircraft have the potential to allow seven crewmembers to breathe off a system designed for four.

Hypoxia training to ensure crewmembers are better capable of recognizing their own hypoxia symptoms, working knowledge of the aircraft oxygen systems, and following the appropriate aircraft checklists and command guidance should prevent most hypoxia-related physiologic incidents. Always:

- Preflight oxygen equipment, both aircraft and personal.
- Perform before takeoff, climb/level off checks.

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Concepts

- Stages of hypoxia
- Symptoms of hypoxia, Table 3.2.10-2.
- Treatment of hypoxia

Vocabulary

- Acclimatization
- Anoxia
- Compensatory stage
- Critical stage
- Diffusion
- Disturbance stage
- Indifferent stage
- Hypoxia
  - Histotoxic hypoxia
  - Hypemic hypoxia
  - Hyperventilation
  - Hypoxic hypoxia
  - Stagnant hypoxia
- Oxygen paradox
- Transportation
- Utilization
- Ventilation

3.3. Oxygen Toxicity

James T. Webb, Ph.D.

3.3.1. Symptom Development

As life forms that have evolved in an atmosphere containing less than about 35% oxygen for the past few million years, we had no need to maintain the biochemistry to handle higher levels of oxygen. Oxygen toxicity results from too much oxygen for too long. Oxygen partial pressure and duration of exposure are variables that affect development of oxygen toxicity symptoms. After several hours of breathing 100% oxygen at sea level (760 mmHg partial pressure of oxygen), symptoms of substernal discomfort associated with oxygen toxicity will develop in most people. However, a National Aeronautics and Space Administration (NASA) study reported that breathing 100% oxygen at 11,500 ft (493 mmHg partial pressure of oxygen) did not result in any symptoms of oxygen toxicity (Webb et al., 1991). Therefore, breathing 100% oxygen above 12,000 ft (a partial pressure of oxygen less than 493 mmHg) is not likely to result in symptoms of oxygen toxicity. Aside from some discomfort associated with breathing dry aviator's oxygen and fire hazards associated with use of 100% oxygen, acceleration atelectasis is the main concern (see Mission-Imposed Effects, Physiologic Effects of Acceleration , section 7.1).

Prevention of hypoxia involves increasing the partial pressure of oxygen in the breathing gas and, at altitudes above 30,000 ft, adding positive pressure breathing. Under these conditions, oxygen toxicity is not likely to occur because the partial pressure of oxygen does not exceed that of sea level air. During unpressurized flight below 10,000 ft and in pressurized cabins during flight below 35,000 ft, oxygen masks are not used unless required, and oxygen toxicity is not an issue. For those missions and type aircraft where oxygen masks are used under those conditions, the amount of supplemental oxygen delivered is insufficient to result in oxygen toxicity. Therefore, oxygen toxicity should not be an issue in Air Force operations.

Some Air Force personnel have been crewmembers on NASA missions where 100% oxygen was used prior to launch at sea level pressure. No effects of oxygen toxicity were recorded for those several-hour exposures. After launch the partial pressure of oxygen was greatly reduced due to the reduction in total pressure to 5.0 psi (259 mmHg). Again, there were no reports of oxygen toxicity symptoms even during long, multiday exposures (Pool, 1998).

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Internet Resources, See Appendix 8.

Vocabulary

Oxygen toxicity

3.4. Trapped Gas

James T. Webb, Ph.D.

There I was, a guy-in-the-back (GIB pilot) of an F-4D coming back from the bombing range at 12,000 ft with no problems…until descent. I began to feel like one of my left upper teeth was about to explode. Clearing my ears did no good. If I'd had a pair of pliers, I think I would have tried to pull it out. The pain couldn't have been worse. I told the front seat pilot who slowed the descent, but we were low enough on fuel that he had to come down. The pain was so bad I banged my head against the canopy with the thought that pain somewhere else might lessen its effect. No good. I even gave serious thought to ejecting, as if that would help, but didn't reach for the handle. Good choice. After the precautionary landing and interview with the flight surgeon, the pain eased and I was sent to a specialist. I had the dreaded nasal polyps. They blocked a maxillary sinus, preventing equalization of pressure during descent to higher atmospheric pressure. The trapped gas had equalized at 12,000 ft, and during descent, the sinus cavity was compressed, putting pressure on a nerve innervating a tooth. Pulling the tooth wouldn't have helped. Surgery did, and it never recurred.

<u>Expansion of trapped gastrointestinal (GI) gas</u> is the most common reason for symptoms arising from gas expansion. The gases are normally expelled during decompression and consist of hydrogen, carbon dioxide, methane, and nitrogen (Tomlin et al., 1991).

3.4.1. Water Vapor and Gas Expansion

The mechanical effects of expansion and contraction of a trapped physiologic gas follow Boyle's Law closely due to the relatively constant temperature of human tissue where gases are located. During decompression (ascent), trapped gases expand because a differential pressure develops as the external pressure decreases. Many trapped gases remain essentially constant in volume due to their structure, e.g., sinuses and the middle ear. Instead of responding by increasing volume, these trapped gases exert a differential pressure on surrounding tissues, which can cause severe, potentially disabling pain and potential physical damage to tissues.

The constant pressure (47 mmHg) of water vapor at body temperature plays an increasing role in gas expansion during ascent as the partial pressures of the other expanded gases decrease.

For example, water vapor makes up only 1% of the volume of a trapped gas bubble at 6 atm ([65 ft of sea water (fsw)] and 6% at sea level but 33% of a trapped gas bubble at 40,000 ft. Due, in part, to the water vapor occupying more of the available pressure in alveoli, PAO_2 becomes extremely low above 45,000 ft. Even with 30 mmHg of additional pressure applied to the lungs via pressure breathing for altitude at 50,000 ft and 60 mmHg of PBA at 60,000 ft, the PAO_2 is the same as breathing air above 18,000 ft. Breathing 100% oxygen with 70 mmHg of PBA at 60,000 ft will provide a PAO_2 equivalent to breathing air at about 15,000 ft, assuming no pressure loss due to mask leakage and sufficient training to allow proper control of breathing. PBA and its effects are discussed in the section on personal equipment effects.

At this writing, no pulse oximetry results have been obtained from humans using current oxygen equipment during exposure to 60,000 ft in an altitude chamber while breathing 100% oxygen with 70 mmHg of PBA (Appendix 1c).

At 63,000 ft, Armstrong's Line, water boils at body temperature. The ambient pressure is 47 mmHg, the same as the partial pressure of water at body temperature. An unprotected human would experience vaporization of tissue water, or ebullism. (Ebullism and embolism are sometimes confused due to the similarity of the terms. Embolism results from respiratory air being forced into the circulation by an overpressure in the lungs.) The altitude or pressure at which ebullism occurs varies with the temperature and pressure in specific tissues. As an example, peripheral tissues are at a lower temperature than internal tissues, and embolism could occur at a lower pressure (higher altitude). Similarly, the higher blood pressure in the arterial system would result in ebullism at lower pressure (i.e., a higher altitude than 63,000 ft). Any artificial increase in pressure around the body lowers the potential for ebullism. A pressure suit increases pressure around the body. PBA keeps the lung at a higher pressure by delivering pressurized breathing gas but does not protect the rest of the body. Current equipment is inadequate to provide sufficient partial pressure of oxygen to tissues above 60,000 ft, even with assisted pressure breathing for altitude (APBA). APBA involves the use of a counterpressure jerkin worn to allow 60 mmHg of pressure to be tolerated for more than a couple minutes.

3.4.1.1 Effects of Trapped Gases During Pressure Change. Since the volume of a sphere is a function of the cube of its radius and the diameter only twice the radius, a large volume change represents a relatively small change in diameter. This is shown in Figures 3.4.1-1a and 3.4.1-1b). However, it is the pressure differential, not volume change, that results in most of the effects listed below.

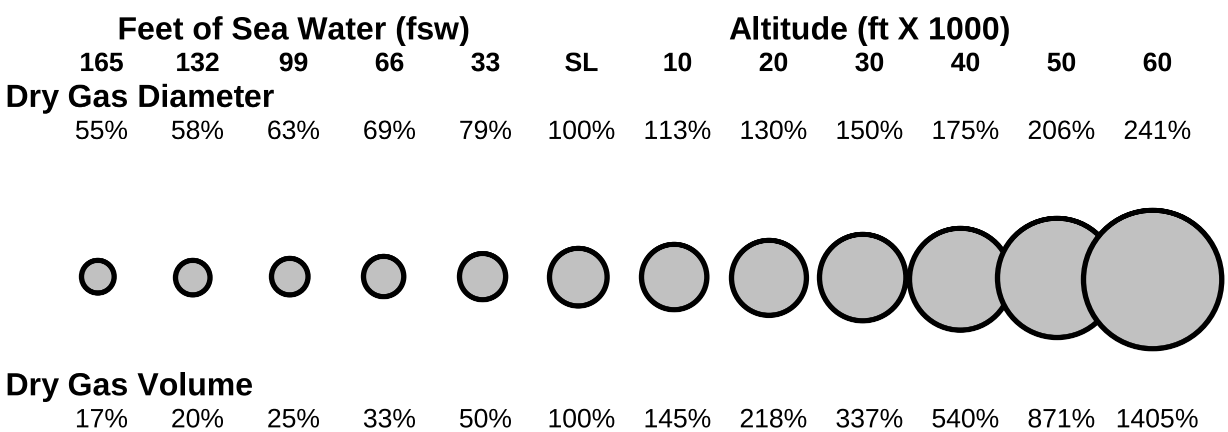

Figure 3.4.1-1a. Change in Volume and Diameter of a DRY Gas Sphere at Different Pressures, Relative to Sea Level

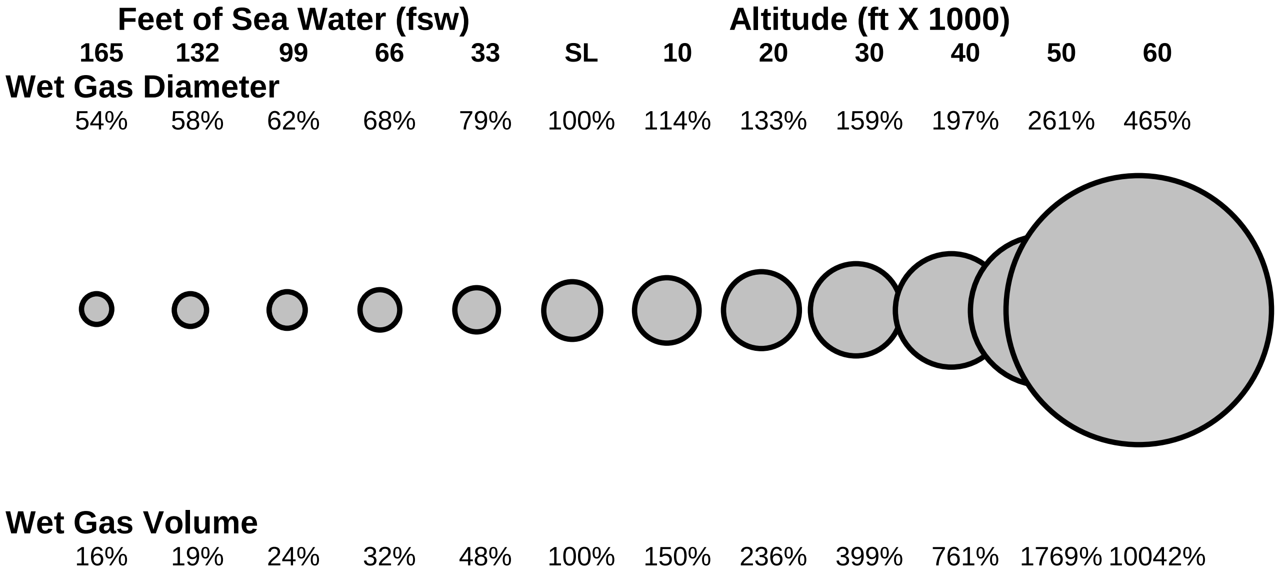

Figure 3.4.1-1b. Change in Volume and Diameter of a WET Gas Sphere at Different Pressures, Relative to Sea Level

- Expansion of trapped gastrointestinal gas. There is always some gas in the large intestine, and during a GI illness, there may be gas in the small intestine, also. Intestinal gas is produced by resident bacteria in the gut. These bacteria are important in maintaining health and normal gut function, which is why antibiotic treatment often produces GI side effects. However, the bacteria produce gases including methane and sulfur dioxide as by-products. In accordance with the gas laws, bubbles of gas in the GI tract expand with altitude. This can cause discomfort, which may be severe. Treatment is to expel the gas, if possible, and, if not, to descend. Prevention involves limiting intake of high-fiber foods before flights. This is in direct contradiction to general health advice to eat more fiber on a regular basis. Increasing fiber consumption for health benefits should be done slowly to allow the gut to adjust, and fiber intake should be limited for 6 hr prior to an unpressurized flight. Gas trapped in the stomach will also expand. The most common cause for stomach gas is intake of gas in the form of carbonated (soda pop) or aerated (milk shake) beverages.
- Ear block, or barotitis media, may be defined as an acute or chronic traumatic inflammation of the middle ear produced by a pressure differential (either positive or negative) between the air in the tympanic cavity and contiguous air spaces and that of the surrounding atmosphere. To equalize the pressures during descent where a pressure differential typically develops, an aircrew member must physically do something to aid equalization across the tempanic membrane (the ear drum). The Valsalva maneuver increases the nasopharyngeal pressure against a closed Eustachian orifice (Fig. 3.4.1-2) to force air into the middle ear: Pinch your nose and blow while your mouth is closed. The Frenzel maneuver may also be performed by thrusting the jaw forward to open the Eustachian tubes, thereby providing a path for equalization of pressure. Both of these maneuvers introduce air to the middle ear. The Valsalva or Frenzel maneuvers may also be used while breathing air after breathing 100% oxygen to avoid pain from delayed ear block. They do so by introducing air containing 79% nitrogen that is not absorbed by surrounding tissues. The differential pressure involved in

delayed ear block is middle ear atelectasis and is caused by absorption and utilization of 100% oxygen by the surrounding tissue. Nitrogen is not utilized by body tissues, and introducing it to the middle ear reduces the differential pressure between the middle ear and ambient pressure.

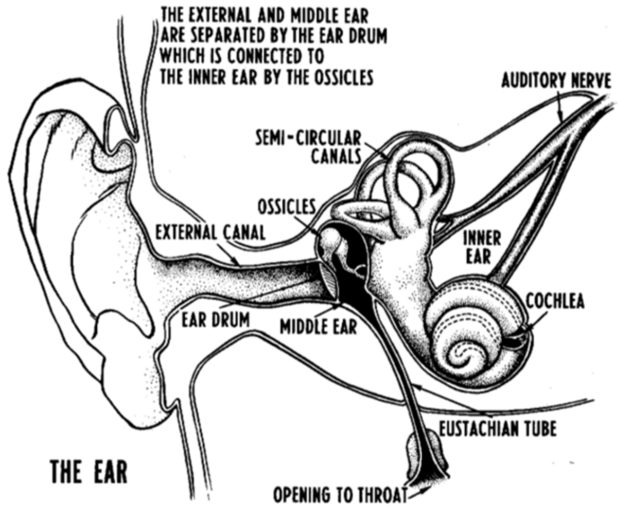

Figure 3.4.1-2. Anatomy of the Ear

Delayed ear blocks sometimes occur after breathing enriched or 100% oxygen. The gas trapped in the middle ear may be very high in oxygen, which is slowly absorbed by the surrounding tissue. This results in negative pressure in the middle ear compared with the external ear. The nitrogen portion of the ambient gas introduced by the Valsalva or Frenzel maneuvers is inert, and if equalization is performed several times during the hours after flight the composition of gases in the middle ear will be returned to normal. The Valsalva and Frenzel maneuvers are only effective if the Eustachian tubes are not blocked. A cold or upper respiratory infection (URI) causes swelling and secretion of mucous. Both of these can block the Eustachian tubes and prevent their normal function of equalization between the atmosphere and the middle ear, hence the recommendation to avoid flying with a cold.

While middle ear block is the most common type, it is possible to get an external ear block. This occurs when a tight-fitting ear plug without a vent is worn through pressure changes. Such ear plugs will always have a vent if they are to be used in flight, but the vent may become blocked with ear wax or other debris. Expanding gas will push past the plug on ascent without difficulty, but on descent the contracting gas will pull the plug in deeper into the external ear canal and will result in a tight seal with a negative pressure on the external surface of the tympanic membrane. It is important to distinguish this from middle ear block because the Valsalva maneuver is the wrong treatment. The Valsalva results in increased pressure in the middle ear, which in the case of the external ear block increases the pressure differential across the tympanic membrane and can cause its rupture. The Frenzel maneuver works for both middle and external ear block and should be stressed as the best way to treat ear block for those wearing tight-fitting ear plugs.

- Sinus block, or barosinusitis, is an acute or chronic inflammation of one or more of the nasal accessory sinuses produced by a pressure difference (usually negative) between the air in a sinus cavity and the surrounding atmosphere. Sinus cavities include the maxillary (cheekbones), frontal and sphenoid (forehead), and mastoid (the bony projection behind the ear). Pressure is usually equalized through drainage passages, but a cold or URI may cause swollen mucous membranes and/or secretion of mucous, blocking the small drainage passages and preventing pressure equilibration. The condition is characterized by pain in the affected region; this pain can develop suddenly and be so severe that the individual will be incapacitated. Treatment in flight is limited to the Valsalva maneuver discussed under ear block and the use of short-acting antihistamine nasal spray. Antihistamine nasal spray is considered an emergency measure and should never be used preventively, as these drugs cause a rapid buildup of tolerance resulting in swollen mucous membranes, leading to greater, rather than lesser, risk of sinus block. A sinus block may also result in tooth pain during descent due to nerves leading through sinuses to the teeth.
- Tooth pain, or barodontalgia, is also a case of a trapped gas exerting positive or negative pressure on surrounding tissue. Rarely, a bubble can be seen on x-ray in the vicinity of an affected tooth, but more often there is no obvious source of pressure. It is believed that microbubbles trapped in small fractures or under a recent filling may be enough to exert pressure on the nerve in the tooth pulp. Tooth pain can also be caused by maxillary polyps that block sinus equalization, resulting in sinus block that can exert pressure on a nerve leading to a tooth.
- Lung overinflation due to breath-hold or inadequate equalization of pressure during decompression can result in serious problems (see section 3.2.6).
  - Pulmonary overexpansion
    - Pulmonary embolism (air in arterial circulation)
    - Pneumothorax (air in pleural cavity)
    - Pneumomediastinum (air in the mediastinum)

3.4.1.2 Treatment.

Ear and sinus pain

- Pain on descent
    - Level off and try a Valsalva.
    - Climb to relieve pressure.
    - Try a Valsalva and decrease descent rate.
    - Consider using Afrin or other vasoconstrictor.
    - Declare an IFE (in-flight emergency)?
    - Land as soon as practical.
- Pain on ascent
  - DESCEND!!
  - Land as soon as practical.

Tooth pain

  - Descend and see a flight surgeon/dentist.
- GI tract pain
  - Release the gas and/or descend.

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Concepts

- Expansion of trapped gastrointestinal (GI) gas
- Armstrong's Line
- Delayed ear block

Vocabulary

- Eustachian tubes
- Valsalva maneuver
- Sinus block
- Pulmonary overexpansion
- Barodontalgia, tooth pain
- Ebullism

3.5. Altitude Decompression Sickness

James T. Webb, Ph.D.

1670	Sir Robert Boyle published his findings concerning bubbles he observed in animal tissue resulting from decompressions of animals using a pneumatic pump (Davis, 2008).
1672	Boyle describes the escape of bubbles in liquids during decompression as causing alteration in circulation (symptoms) (Bert, 1878).
1906	H. von Schrötter describes symptoms experienced in a steel chamber after ascending to 8,994 m (29,500 ft) in 15 min. The symptoms closely resembled those occurring when caisson workers decompressed to surface pressure (caisson disease) (von Schrötter, 1906).
1908	J.S. Haldane's seminal paper on decompression sickness prevention during caisson work (Boycott et al., 1908).
1917	First clear reference to altitude DCS in the literature where Henderson described a detailed theory in which he postulated that it would be possible to get decompression sickness from altitude exposure (Henderson, 1917).
1931	A description of pain in the knees experienced in a hypobaric chamber while doing a step exercise at 9,160 m (30,000 ft; 233 mmHg) was most likely a manifestation of DCS, unrecognized as such at the time (Barcroft et al., 1931).
1938	Boothby and Lovelace reported a case of transient paraplegia in a fellow physiologist (Dr. J.W. Heim) during an ascent to 10,670 m (35,000 ft) while on oxygen; the paraplegia disappeared upon repressurization to ground level. This case illustrated the potential for serious neurological DCS at altitude (Boothby & Lovelace, 1938).
ca1939	Armstrong researched the effects of decreased barometric pressure on the aviator and described bubble formation that he experienced himself while at altitude in the hypobaric chamber (Engle & Lott, 1979): "I wound up with the classical symptoms. My hands began to feel stiff and slightly sore and I massaged them, trying to improve the circulation. Then I noticed a series of small bubbles in the tendons of my fingers. I could actually feel them, and by manipulating my finger along my tendon I could squirt these bubbles back and forth. I was certain in my own mind they represented aeroembolism, but it was not positive proof."
1947	Behnke postulated the existence of "silent bubbles," which are present in tissues and blood yet do not cause symptoms (Behnke, 1947).
1959	The School of Aviation Medicine (which had just moved from Randolph Air Force Base (AFB) to Brooks AFB) became part of the USAF Aerospace Medical Center.
1963	On 21 Nov 1963, President John F. Kennedy visited Brooks AFB to dedicate a new complex of buildings added to the USAF School of Aerospace Medicine (USAFSAM), including an altitude research chamber where the photograph below was taken (Fig. 3.5-1). He was assassinated less than 24 hr later (Stepanek & Webb, 2008).

Figure 3.5-1. President Kennedy Visiting Research Altitude Chamber at USAF School of Aerospace Medicine

1976	Merrill Spencer publishes a method to grade intravascular bubbles, venous gas emboli (VGE) heard during ultrasonic monitoring of the heart following decompression (Spencer, 1976).
1990	Laboratory function of USAFSAM incorporated into the Armstrong Laboratory at Brooks to become one of the four "super labs" of the Air Force Systems Command (AFSC) on 13 Dec 1970 (AFSC History Publication).
1997	The Air Force Research Laboratory, which was created to incorporate all AF laboratories, including the Armstrong Laboratory, in a single AF laboratory, was formally activated on 22 Oct 1997 (AFSC Historical Publication).
2005	Cancellation of high-altitude research in the USAF facilities at Brooks City-Base.

Decompression sickness was referred to in the 1940s and earlier as the bends, dysbarism, caisson disease, compressed-air illness, staggers, etc. Altitude <u>decompression sickness</u> refers to that malady occurring during some aviation and space endeavors in which gas bubbles are formed during decompression from surface or vessel pressure to a subatmospheric pressure. Bubbles can form in fluids at low levels of supersaturation if forces act to pull objects apart that are in close proximity, a process called tribonucleation (Ikels, 1970).

DCS can result when pressure is reduced on body fluids saturated with inert gas. At ground level, tissues and blood are always saturated with nitrogen, an inert gas. Since nitrogen gas is not metabolized by the body tissues (inert), its concentration in the tissues is only a function of its partial pressure in the breathing gas and its solubility in the body tissues. When the tissues become supersaturated with nitrogen during decompression to altitude, the nitrogen may not diffuse into the capillaries and be exhaled before it forms bubbles. This process is analogous to the bubbles formed when a carbonated beverage is opened, resulting in a pressure reduction that occurs faster than the carbon dioxide can diffuse out of the fluid, also forming bubbles. The bubbles

of nitrogen (containing some carbon dioxide, oxygen, and water vapor) can interact with the surrounding tissue and blood by exerting local pressure. The pressure can slow or block blood flow and stimulate responses by sensory nerves. Bubbles in venous circulation are usually cleared effectively in the lungs. Rarely, bubbles pass through the lungs, entering the arterial circulation, and can cause serious symptoms as arterial gas emboli.

Extravascular bubbles, tissue bubbles, can cause symptoms. The existence of bubbles in and of itself is not DCS; DCS refers to the maladies caused by the bubbles. DCS symptoms are highly diverse.

3.5.1. Symptoms of DCS

The symptoms of DCS can cause distraction and may interfere with optimal function. They can also be more serious, involving respiratory or neurologic function, resulting in severe loss of performance, abort of a flight mission, and requirement for hyperbaric oxygen therapy to achieve resolution. There are four categories of DCS symptoms:

- Limb Pain – Typically joint or muscle pain (70%-84% of all altitude DCS symptoms) (Balldin et al., 2002, 2004; Ryles et al., 1996); most common DCS symptom.
- Skin – Mottling, pins & needles, tingling, prickling (about 13% of all altitude DCS symptoms) (Ryles et al., 1996); second most common DCS symptom.
- Neurologic – Cold sweat, dizziness, edema, inappropriate or sudden onset of fatigue, headache, light headedness, loss of consciousness, motor and/or sensory loss, nausea, tremor (shakes), vertigo (1%-8% of all altitude DCS symptoms) (Balldin et al., 2004; Ryles et al., 1996; Clark, 1992).
- Respiratory (pulmonary) – Cough, dyspnea (difficult or labored breathing), substernal distress (tightness and/or pain in chest, especially during inspiration) (about 3% of all altitude DCS symptoms) (Balldin et al., 2002; Ryles et al., 1996).

DCS symptoms have been categorized as Type I, pain-only symptoms, and Type II, serious symptoms, since introduction of the nomenclature in 1960 by Golding et al. (1960). This categorization was created to separate the symptoms into groups based on their response to treatment. The symptoms developed during or after decompression from caisson work on the Dartford Tunnel in England. This system was somewhat analogous to the four-table treatment scenarios used at that time by the U.S. Navy as described by Donnell & Norton (1960). The four hyperbaric treatment tables (I-IV; I-A & II-A without oxygen available) involved treating increasing symptom severity with more aggressive hyperbaric profiles. The dichotomous Type I/II separation of symptoms does not provide sufficient information for U.S. Air Force physicians to adequately diagnose altitude DCS and prescribe treatment, although it is still in common use for describing diving DCS(Moon & Sheffield, 1997). The U.S. Navy uses the Type I and Type II categories of DCS for the Master Diver to determine treatment of diving DCS. The Master Diver provides HBO treatment as needed for USN divers in the absence of a physician, creating a need for clear guidelines regarding treatment. USAF physicians determine treatment for altitude DCS based on the symptoms and their severity. An accurate description of a case of altitude DCS involves stating the evolution of each symptom (Francis, 1992):

- spontaneously resolving
- static
- relapsing
- progressive

Each symptom should be stated with the time interval from its onset to the commencement of treatment. "Progressive, limb-pain DCS occurring 1 hr prior to commencement of treatment" would provide essential information to a USAF flight surgeon for use in determining treatment, unlike "Type I DCS." The timeline of any relapsing or progressive symptoms should be further described to include an indication of change and level of intensity. In addition, the response to recompression should be indicated (complete recovery, incomplete recovery, or none) to guide any further treatment options.

- Symptom evolution. A report from research chamber studies using well-documented symptom onset and resolution information (Muehlberger et al., 2004) discussed DCS resolution in 1096 cases of DCS observed during research exposures at Brooks. Of that group, 76 cases, 6.9%, were treated with HBO to resolve symptoms or as a precautionary measure. The remaining 1020 cases were not treated with HBO and completely resolved before arrival at ground level or before treatment was deemed necessary. All but one of the 15 cases involving precautionary treatment also involved HBO treatment to resolve another symptom. This indicates that most altitude DCS symptoms resolve during descent and do not require any additional treatment.
- <u>Altitude vs. diving DCS.</u> Due to frequent misconceptions regarding the similarities and differences between altitude and diving DCS, Table 3.5.1-1 is provided to clarify the major differences between the two environmental hazards (Pilmanis et al., 2004).

3.5.2. Treatment of DCS

Since many physicians have no training in recognition or treatment of altitude DCS, it is important for aircrew to be aware of the symptoms of DCS and the need to seek medical attention from informed personnel. Altitude DCS is typically resolved during descent to a lower altitude while breathing 100% oxygen in accordance with current USAF directives. Continued breathing of 100% oxygen on the ground for 2 hr is usually effective treatment for mild cases of DCS that do not resolve completely during descent (Krause et al., 2000). The reason for resolution of symptoms with this procedure is twofold: (1) the gas emboli (bubbles) are subjected to increased pressure during descent, which will reduce their size and effect (Muehlberger et al., 2004); and (2) breathing 100% oxygen partially denitrogenates blood and tissues. This reduces the potential for bubble growth and results in shrinkage of existing bubbles in tissues adjacent to capillaries, where the diffusion gradient will favor nitrogen leaving the tissue and entering the denitrogenated blood.

Table 3.5.1-1. Major Differences Between Diving and Altitude Decompression Sickness

Altitude DCS	Diving DCS
1. Decompression starts from a ground level tissue N_2 saturated state.	1. Upward excursions from saturation diving are rare.
2. Breathing gas is usually high in O_2 to prevent hypoxia and promote denitrogenation.	2. Breathing gas mixtures are usually high in inert gas due to oxygen toxicity concerns.
3. The time of decompressed exposure to altitude is limited.	3. The time at surface pressure following decompression is not limited.
4. Pre-mission denitrogenation (preoxygenation) reduces DCS risk.	4. The concept of preoxygenation is generally not applicable.
5. DCS usually occurs during the mission.	5. DCS risk is usually greatest after mission completion.
6. Symptoms are usually mild and limited to joint pain.	6. Neurological symptoms are common.
7. Recompression to ground level is therapeutic and universal.	7. Therapeutic chamber recompression is time limited and sometimes hazardous.
8. Tissue PN_2 decreases with altitude exposure even while breathing air.	8. Tissue PN_2 increases with hyperbaric exposure while breathing air.
9. Metabolic gases become progressively more important as altitude increases.	9. N_2 dominates.
10. There are very few documented chronic sequelae.	10. Chronic bone necrosis and neurological damage have been documented.

3.5.3. HBO Therapy

The following are the USAF procedures if DCS is suspected:

- 100% oxygen
- Descend as soon as practical
- Declare IFE
- Land at the nearest airfield with qualified medical assistance (military flight surgeon or civil aeromedical physician) available

Hyperbaric oxygen therapy is the standard of DCS care, and it is successful in treating DCS symptoms that do not resolve before landing or which involve neurologic or pulmonary (respiratory) symptoms. The additional pressure of the hyperbaric treatment further reduces the size of existing bubbles. Breathing of 100% oxygen during the HBO treatment ensures no further nitrogen is delivered to the tissues and helps to oxygenate tissues where bubbles may have blocked delivery of oxygenated blood. HBO treatment of DCS, whether from altitude or hyperbaric exposures, has been documented to be more successful if begun as soon as practical after symptoms appear. When symptoms are reported later, treatment is not as effective. The nature and severity of the symptoms dictate the specific hyperbaric profile for treatment and may require multiple treatments for complete resolution. The USAF School of Aerospace Medicine's Hyperbaric Medicine Division (USAFSAM/FEH) serves as the primary source of information and consultation on treatment of DCS for the USAF.

Treatment of USAF altitude chamber reactors is guided by USAFSAM/FEH directives based on time since treatment and the symptoms at time of treatment. Some treatment scenarios involve ground level oxygen and the rest utilize hyperbaric oxygen therapy. HBO treatment scenarios include modified USN Treatment Table 5 and 6 profiles to 60 fsw breathing 100% oxygen with air breaks to avoid oxygen toxicity. The profiles last from 135 to 285 min not including descent time. Treatment Table 6A to 165 fsw for 319 min is employed for treating air embolism and only rarely for DCS cases that do not resolve with Treatment Tables 5 or 6. At 165 fsw, air or a nitrox mix is used to prevent oxygen toxicity. Due to the renitrogenation that takes place at 165 fsw and the relatively small reduction in bubble size with the extra pressure (see Figure 3.4.1-1b), Table 6A is generally not considered a good choice for treatment of DCS. The algorithm to assist in treatment shown in Table 3.5.3-1 was developed at the USAFSAM Hyperbaric Medicine Division.

Of the nearly 1000 cases of DCS observed in subjects during 20 yr of altitude DCS research chamber activity at Brooks AFB (City-Base), 89 subjects were treated with HBO by the Hyperbaric Medicine Division, all with complete resolution of symptoms. The remaining cases were successfully treated with 2 hr of ground level oxygen (Krause et al., 2000) or with no treatment.

Disposition of aircrew who develop DCS is described fully in Air Force Instruction (AFI) 48-123v3. The large majority of cases are treated successfully and returned to flying status. Grounding for 72 hr after any treatment is standard, although any residual symptoms receive further evaluation and potential waiver or permanent grounding.

3.5.4. Factors Affecting Incidence of DCS

The factors that affect DCS incidence are extensive and involve both the environment and the individual exposed. The <u>four primary factors that affect DCS incidence</u> are altitude, time at altitude, prebreathe time, and level of activity.

- *Environmental Factors:*

  - Altitude. The higher the altitude, the higher the incidence of DCS once the threshold altitude is achieved. The threshold altitude for 5% DCS during 4-hr zero-prebreathe exposures with mild exercise was shown to be a little under 20,000 ft (see Webb et al., 2003; Pilmanis et al., 2003). Above 20,000 ft, the incidence of DCS increases exponentially to 80% by 25,000 ft. Research (Webb et al., 2003; Haske et al., 2002) has indicated that exposures above 20,000 ft without prebreathe would involve significant DCS risk if not limited in duration. DCS has occurred below 20,000 ft, although the incidence is so low as to be operationally insignificant (Webb et al., 2003).

Table 3.5.3-1. Management of Altitude Decompression Sickness

Carefully assess DCS symptoms
1. Joint pain or skin symptoms only; A-D; not, 2. A. Symptoms present in less than 2 hr? Surface level oxygen Worsen or fail to improve? Treatment Table 5 Worsen or fail to improve? Treatment Table 6 Worsen or fail to improve? Consider extensions or Treatment Table 6A and tailing dives until resolve or symptoms plateau
B. Symptoms present in 2 to 6 hr? Treatment Table 5 Worsen or fail to improve? Treatment Table 6 Worsen or fail to improve? Consider extensions or Treatment Table 6A and tailing dives until resolve or symptoms plateau
C. Symptoms present > 6 hr? Treatment Table 6 Worsen or fail to improve? Consider extensions or Treatment Table 6A and tailing dives until resolve or symptoms plateau
D. Symptoms present > 36 hr? Reconsider diagnosis of DCS
2. Neurologic, pulmonary, or cardiac symptoms Treatment Table 6 Worsen or fail to improve? Consider extensions or Treatment Table 6A and tailing dives until resolve or symptoms plateau

Figure 3.5.4-1 shows results of 113 male and 80 female 4-hr exposures with mild, upper-body, ambulatory exercise (Webb et al., 2003). Each subject was exposed one time, allowing a probit curve to show the relationship between altitude and incidence (Webb et al., 2003). DCS occurs below 20,000 ft, although the incidence is so low as to be operationally insignificant with the probit curve showing less than 1.03% DCS at 18,000 ft and less than 0.01% DCS at 14,400 ft. The incidence of venous gas emboli is also shown as a corollary of exposure severity versus altitude, although VGE detection as a predictor of DCS is poor. The sigmoidal relationship between exposure altitude and DCS incidence (Figs. 3.5.4-1 and 3.5.4-2) illustrates why exposures to 35,000 and 40,000 ft with up to 90 min of prebreathe do not result in 100% DCS (Webb et al., 2001; Pilmanis et al., 2003). Although

much higher onset rates of DCS occurrence were observed at successively higher exposure altitudes up to 25,000 ft (Fig. 3.5.4-1; Webb et al., 2003), no DCS was observed within 15 min. The onset curves did indicate a higher rate of symptom onset with increasing altitude.

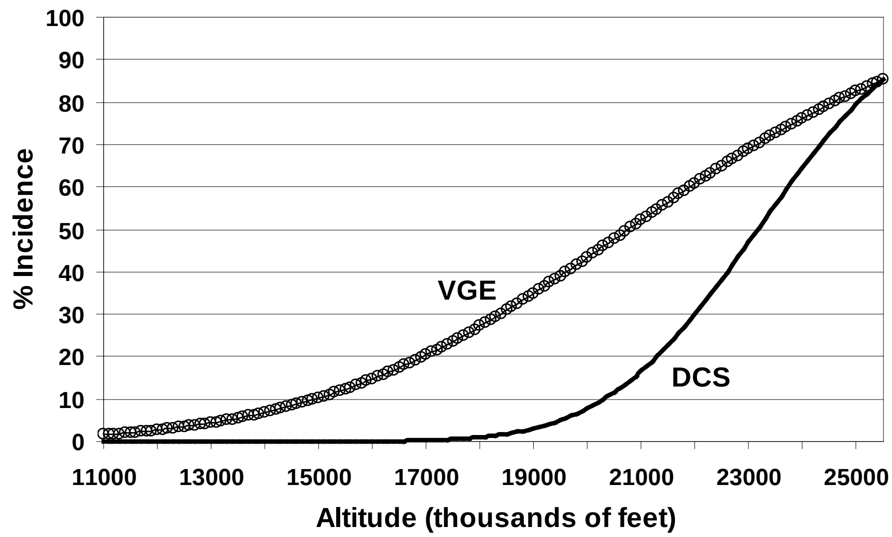

Figure 3.5.4-1. VGE and DCS During 4-hr, Zero-Prebreathe Exposures of 193 Male (113) and Female (80) Subjects Performing Mild Exercise and Breathing 100% Oxygen During Exposure

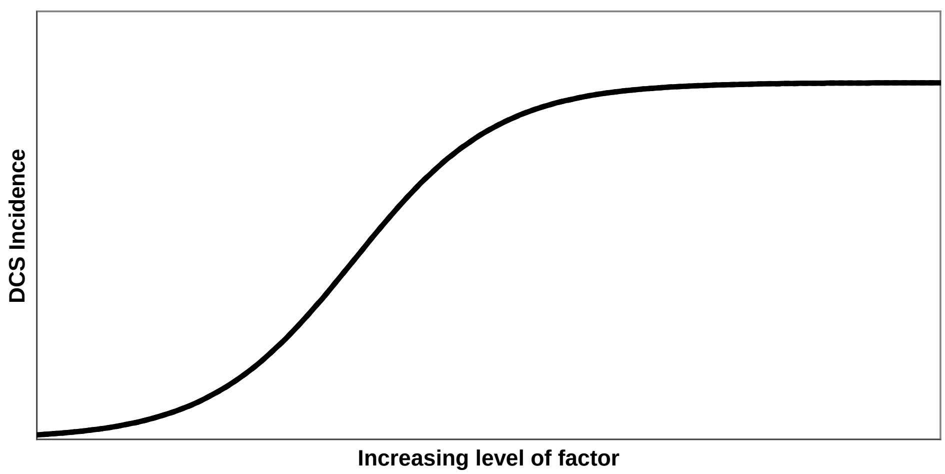

Figure 3.5.4-2. Sigmoidal Relationship of Increasing Risk Factor with Increased DCS Risk (Source: Webb & Pilmanis, 1995)

- Time at altitude. The longer the exposure time, the higher the incidence of DCS. However, there is a lag time before symptom onset that makes very brief exposures relatively safe, e.g., rapid decompression followed by immediate descent on 100% oxygen (Webb & Pilmanis, 1995), as would occur in a rapid decompression in which aircrew successfully follow their emergency procedures.

Risk factors of both altitude and time at altitude (other factors kept constant) reveal a sigmoidal relationship with DCS incidence when plotted as in Figure 3.5.4-2.

- *Level of Activity*. Level of activity has a significant effect on DCS risk depending when it is done (before, during, or after exposure to altitude) and what level of activity is performed.

  - Before exposure, exercise can have a beneficial effect if accomplished during prebreathe (see Prebreathe – Exercise during prebreathe below).
  - During exposure, higher levels of activity result in higher levels of DCS and can be a very significant factor in overall incidence (Gray & Masland, 1946; Pilmanis et al., 1999; Webb & Pilmanis, 1995; Webb et al., 2001, 2010a&b). This does not appear to be related to the type of activity (isometric vs. dynamic, arm vs. leg) (Pilmanis et al., 1999) or whether walking is part of the activity (Webb et al., 2005). Also, lower levels of activity result in onset curves, which may not indicate the DCS risk levels even after 4 hr of exposure as shown in Figure 3.5.4-3. The total incidence of DCS while decompressed appears to be related to the oxygen consumption (metabolic rate) during the highest 1 min of activity repeated during an exposure as shown in Figure 3.5.4-4 (Webb et al., 2010a).

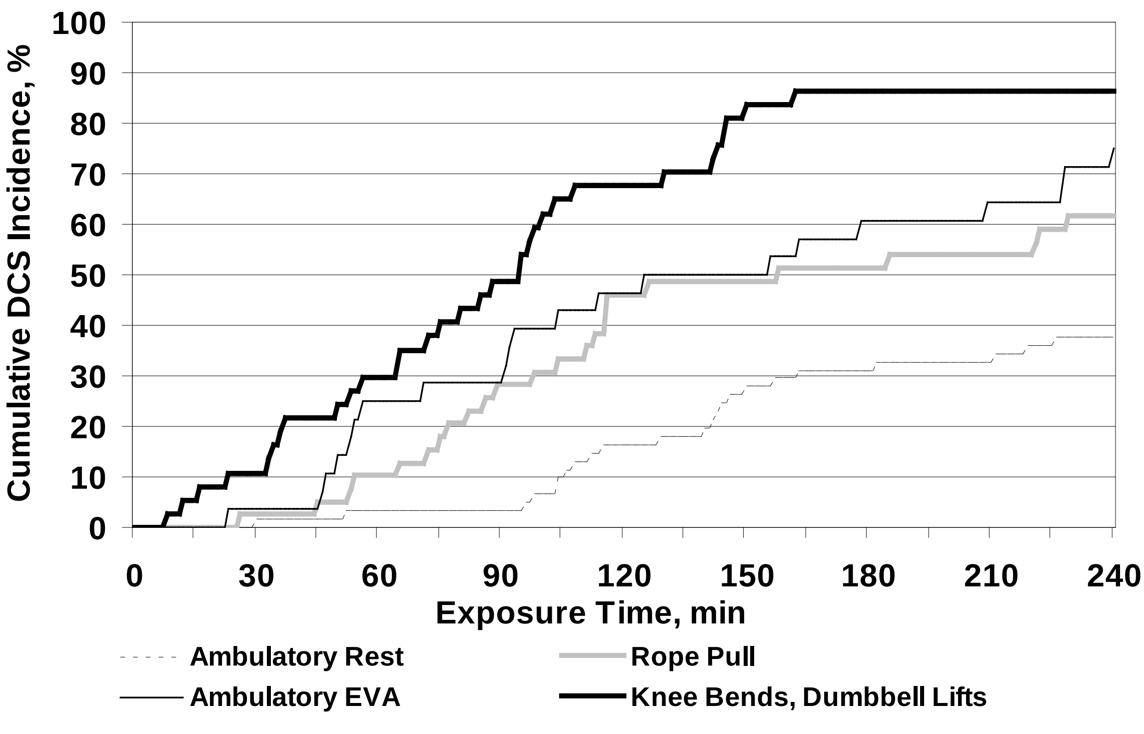

Figure 3.5.4-3. Cumulative DCS Incidence in Altitude DCS Research Exposures to 30,000 ft for 4 hr Following 1 hr of Resting Prebreathe While Performing Different Activities

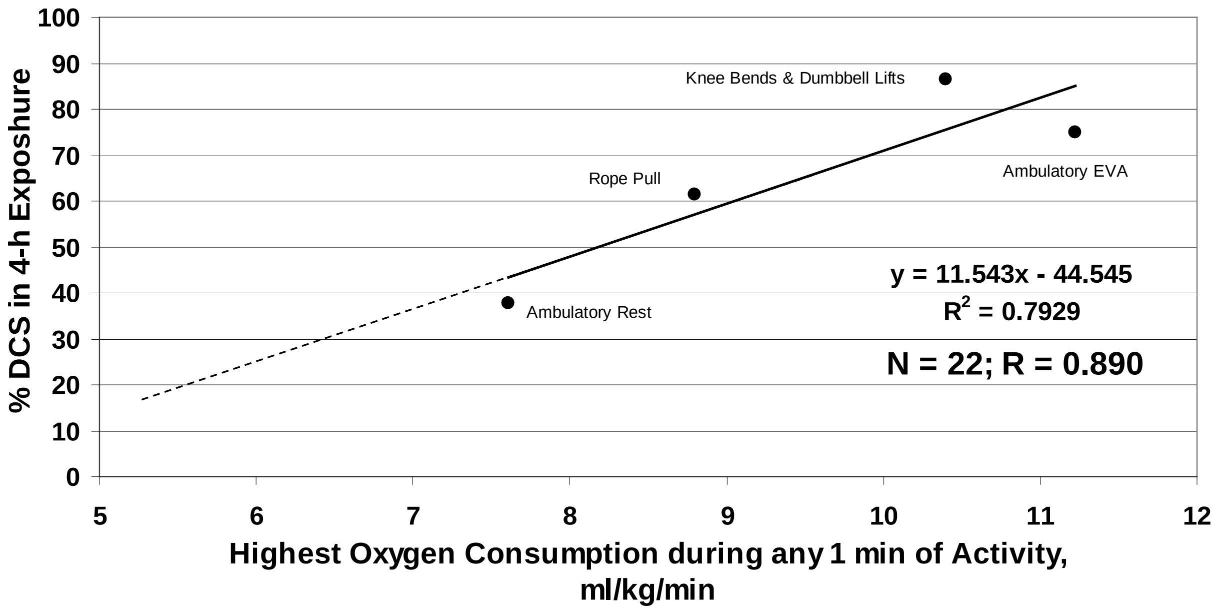

Figure 3.5.4-4. Relationship of Oxygen Consumption to DCS Incidence with All Other Conditions Constant (29,500-30,000 ft; 4-hr exposure; 1-hr prebreathe)

- After exposure. Exercise following a decompression exposure was shown to involve no more risk than resting after exposure (Webb et al., 2002b). However, exercise-induced pain may be misdiagnosed as DCS pain, or vice versa in the case of latent/delayed DCS. It is therefore advised to avoid strenuous exercise for 12 hr after altitude chamber training.

- *Prebreathe*. Reduction in the level of nitrogen dissolved in body fluids and tissues reduces the potential for supersaturation, bubble formation, and resulting symptoms of DCS. Nitrogen can be eliminated from the body by breathing 100% oxygen before decompression, a process variously called prebreathe, preoxygenation, or denitrogenation. This is a method of reducing DCS risk and is common practice when other methods are not practical. Prebreathing works because there is more nitrogen dissolved in the blood flowing into the lung capillaries than there is in the adjacent alveoli. The alveoli, when breathing 100% oxygen, contain no nitrogen, allowing diffusion of nitrogen from the capillaries into the alveoli where it is exhaled. For several current operational mission scenarios it is required (Air Combat Command Instruction (ACCI) 11-459; AFI 11-409; Army Regulation (AR) 95-1; Field Manual (FM) 3-04.301; Internet Resources, see Appendix 8).

- Prebreathe time. Longer prebreathe, or denitrogenation time, results in less DCS, although each additional hour of prebreathe produces less protection than the hour before it (Waligora et al., 1987; Webb et al., 2002a). Generally, greater DCS risk is mitigated by longer prebreathe, but the relationship is not linear (Fig. 3.5.4-5. Although effective, the time consumed while prebreathing also becomes an operational factor due to crew duty day limitations and thermal considerations depending upon conditions where the prebreathe occurs. During U-2 operations, a pressure suit is required because loss of pressurization at operational altitudes

without such protection would not allow successful recovery. The pressure suits are movement restrictive and are not normally pressurized during flight. Since the U-2 pressurization system is inadequate to provide protection from DCS at operational altitudes without pressurization of the suit, there is a requirement for at least 1 hr of prebreathe. Some individuals require more prebreathe time to avoid serious symptoms, limiting the crew duty day remaining and potentially limiting their operational effectiveness (Bendrick et al., 1996).

- <u>In-flight denitrogenation</u>. In lieu of breathing 100% oxygen prior to takeoff, breathing enriched oxygen while airborne at a cabin altitude below which DCS is a concern, staged decompression, can provide efficient denitrogenation (Webb et al., 2000). The practical upper altitude limit for efficient use of this method appears to be *16,000 ft*. Merely living at an altitude well above sea level provides some protection because the partial pressure of N_2 in the body is reduced. Adler (1964) summarized Haldane's (1908) work on staged-ascent denitrogenation by stating that greater denitrogenation efficiency occurs during ascent as a result of increasing the pressure gradient of nitrogen from inside to outside the body. Testing for susceptibility to DCS in chambers situated at 4700 ft resulted in only one rejection in 28 trainees exposed on multiple occasions. The 4% rejection rate was far below the 35% DCS incidence reported using chambers situated near sea level (Cheetham, 1947). Clark et al. (1960) discussed denitrogenation by living at an altitude of 10,000 ft (525 mmHg) or after 2 days at 14,160 ft. Balke (1959) stated that residence at 14,160 ft for 2 days followed by decompression to 38,000 ft resulted in [Grade 2 DCS joint pain] slight, easily tolerable pains that disappeared toward the end of the 1-hr test involving five deep knee bends performed at regular intervals. “The protective effect of the partial denitrogenation at an altitude of 14,000 feet was also confirmed in experiments in which the subjects were exposed to altitudes between 42,000 to 56,000 feet for a total time of 30 to 40 minutes.” “There were <u>no</u> symptoms of decompression sickness.” “Comparative experiments at sea level had shown that 4 to 6 hours of breathing 100% oxygen did not offer complete protection against decompression sickness.” A staged-decompression has been used since early 2007 on the International Space Station (ISS). Another staged-decompression procedure has been proposed for use during Moon and Mars exploration using the crew exploration vehicle and habitat at the stage pressure (Lange et al., 2005).
- <u>Exercise during prebreathe</u>. Making a given prebreathe duration more effective can be accomplished by increasing heart rate, stroke volume, and ventilation rate by exercise of all major muscle groups during prebreathe with 100% oxygen. Exercise also results in vasodilatation, which increases perfusion to muscle and skin. The consequent increased rate of denitrogenation has been shown to be effective in experimental conditions (Webb et al., 1996) as well as in the operational U-2 environment (Hankins et al., 2000). It was also used, with modification by NASA, to prepare for extravehicular activity (EVA) from the ISS (Woodruff et al., 2000). Beginning in 2001 and until a staged-decompression procedure, in-flight denitrogenation, was developed and used beginning in early 2007, the exercise-enhanced prebreathe procedure was used during 21, two-member

EVAs (42 individual EVAs) from ISS (Dervay J, Personal communication, 12 Jul 2007; Webb et al., 2010b).

    - Break in prebreathe. It was thought for some time that a very short break in prebreathe would have significant effects on DCS incidence, requiring a "make-up" prebreathe. Recent studies showed that a 10-, 20-, or 60-min break in prebreathe significantly increased DCS incidence under laboratory conditions involving 4-hr exposures (Pilmanis et al., 2010). It was suggested "...that a safe limit does exist...," perhaps of 5-min, 3-min, or 1-min duration.

- Rate of ascent. A higher rate of ascent has been implicated as causing more DCS, although a study by Pilmanis et al. (2003) did not find such a relationship when 5,000 fpm and 80,000 fpm were compared during decompressions to 40,000 ft. Although the 80,000-fpm decompressions were much faster, they did not qualify as rapid (2-15 s), and no conclusion could be drawn as to the effect of a "rapid" decompression on DCS incidence. A very slow rate of ascent while breathing 100% oxygen would provide effective denitrogenation and thus confuse the results of a comparison with the more typical rate of ascent of 5,000 fpm used in most USAF chambers and altitude DCS research.
- Repeated exposure. A study of repeated exposures comparing one 2-hr continuous exposure with four 30-min exposures separated by either 0 (bounce recompressions) or 2-hr ground times showed the repeated exposures to have significantly less DCS risk (Pilmanis et al., 2002). Unlike diving, repeated exposures to altitude involve repeated denitrogenation, which reduces the nitrogen in the body and therefore the DCS risk.
- Flying after diving. Nitrogen absorbed by the body tissues while scuba diving increases risk of DCS during an altitude exposure after diving if the interval between the dive and flight is insufficient to allow the additional nitrogen to be expired (Bassett, 1982; Vann et al., 2004). Bruce Bassett's technical report, *Decompression Procedures for Flying After Diving, and Diving at Altitudes Above Sea Level* (Bassett, 1982) reviewed studies conducted at the request of the USAF Aerospace Rescue and Recovery Service, Military Airlift Command, in 1976. The hyperbaric and hypobaric chambers at Brooks were used to test several schedules involving no-decompression dives followed by altitude exposures of 10,000 ft and 16,000 ft (Phase I) and 8,500 ft and 14,500 ft (Phase II). Data from the 160 subject-exposures resulted in recommendations for changes to the U.S. Navy schedules for altitude exposures following diving. The U.S. Navy Standard Air Decompression Tables were revised based on the results.
- Time of day and temperature of exposure. Definitive studies have yet to be done, and conclusive data are not available.

The plot of preoxygenation time versus DCS risk is exponential (Fig. 3.5.4-5), indicating that each additional period of prebreathe is less effective than the previous period. One study showed that complete protection from DCS at 30,000 ft was only achieved after 8 hr of prebreathe (Waligora et al., 1987).

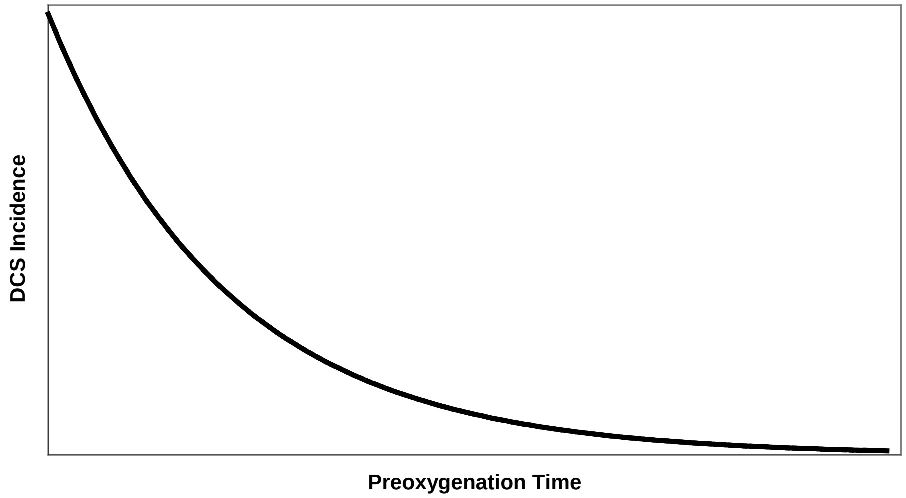

Figure 3.5.4-5. Exponential Relationship of Reduced DCS Risk with Increasing Prebreathe Time (Webb & Pilmanis, 1995)

3.5.5. Individual Susceptibility

Some individuals are resistant and others susceptible to development of altitude DCS. However, they can only be identified by subjecting them to several altitude profiles that have sufficient DCS risk to allow differentiation of susceptibility. Since this is impractical, prediction of an individual's susceptibility based on anthropometric or physiologic parameters was attempted. Although groups of individuals with the following characteristics were shown to be more or less susceptible to symptom development (Webb et al., 2005), using such characteristics to predict susceptibility of any one individual has been unsuccessful:

- Higher body mass index in both males and females was shown to correlate with higher susceptibility to DCS ($P < 0.001$; Webb et al., 2003).
- Lower maximal oxygen uptake (lower physical fitness) in both males and females was shown to correlate with higher susceptibility to DCS ($P < 0.001$; Webb et al., 2003). Since aerobically less fit individuals generally have a lower level of vascularization than those more physically fit, they may not be able to denitrogenate as quickly as the more physically fit.
- Body fat. The logic behind the conventional wisdom that individuals with higher body fat are more susceptible to DCS symptoms is based, in part, on the fact that "…at body temperature the fat of mammals dissolves at least five times as much nitrogen as water or as blood and blood plasma" (Vernon, 1907). Anecdotal evidence and some retrospective studies have supported this view. A recent study reported that the 79 female subjects with higher body fat (highest third) had a higher incidence of DCS than the 83 with lower body fat (lowest third) ($P < 0.03$; Webb et al., 2003). The 479 male subjects so divided did not show any difference in DCS incidence. It must be noted that all subjects were chosen to closely match the USAF aircrew and NASA astronaut corps in body fat percent; thus, the body fat percentages observed were lower than the general population – females, 22.2% $\pm$ 4.4% and males, 16.8%$\pm$ 5.1%.

- Increased age has been cited several times as contributing to DCS susceptibility (see review by Behnke, 1971) and was recently shown to affect males and females in the age range of USAF personnel in different ways (Webb et al., 2003), but it was only significant when the oldest 5-yr group of males was compared to the youngest 5-yr group of males ($P < 0.03$). Increased age is related to lower metabolic rates and generally lower physical fitness, possibly having a negative influence on rate of denitrogenation.
- Weight was shown to be a factor only in males, with the heaviest third being more susceptible to DCS ($P < 0.01$; Webb et al., 2003).
- Gender. Although some studies concluded that females are more susceptible to DCS, others have stated no difference was found. The recent extensive review of prospective research chamber experiments with both male and female subjects showed that gender is not a factor in susceptibility to DCS ($P > 0.23$ with 45% DCS during 309 female exposures and 50% during 550 male exposures). Females were shown to be more resistant to development of bubbles as detected by ultrasound and echo-imaging of the right atrium and ventricle (Webb et al., 2003).
- Height was not shown to be a factor in DCS susceptibility (Webb et al., 2003).
- Dehydration and previous injury. Although dehydration has been suggested as contributing to DCS risk (Cockett et al., 1965), no definitive studies have been accomplished that address that variable. Alcohol consumption frequently results in some degree of dehydration, complicating the anecdotal link of DCS risk with alcohol. Bridge et al. (1944) did not find an effect of previous injury on DCS location.

During World War II (WWII), variations in DCS susceptibility of an individual from day-to-day were greater than between individuals, making efforts to identify DCS-susceptible or DCS-resistant individuals impractical (Gray et al., 1947). Even with more detailed information available now under laboratory conditions with evaluation of more parameters, it is not possible to reliably predict an individual's susceptibility based on anthropometric or physiologic measures (Webb et al., 2005) due to the same day-to-day variations in individual susceptibility.

3.5.6. Prevention of DCS

During the early part of WWII, the incidence of hypoxia and DCS was high due to frequent unpressurized flight above 30,000 ft in the B-17 and B-24. Adequate pressurization of aircraft was shown to be the best answer to both DCS and hypoxia as demonstrated with development and employment of the pressurized-cabin B-29. Hypoxia is normally prevented by proper use of adequate oxygen equipment below 40,000 ft. However, DCS risk remains a current problem above about 20,000 ft. Some of the reasons for DCS risk to be a current issue are operational in nature:

- Occasional loss of pressurization in adequately pressurized aircraft followed by the rare incidence of continued flight at altitudes exceeding about 20,000 ft can lead to DCS.
- Development of aircraft designed to cruise above 50,000 ft, but with inadequate pressurization systems, presents conditions leading to risk of DCS, e.g., the U-2 high-altitude reconnaissance aircraft and the F-22.

- Flight in pressurized aircraft at or above 20,000 ft operated unpressurized for operational reasons or parachute operations can provoke DCS if operational guidelines (AFI 11-409) are not followed.
- Flight in unpressurized aircraft at or above 20,000 ft may result in DCS. The CV-22 is unpressurized and can cruise at 25,000 ft. Without prebreathe, the crew may be at risk of DCS depending on level of activity and duration of such cruise.

Barring use of adequate pressurization, other methods of preventing DCS are likely to impact operational requirements. Such methods include procedures that reduce the risk factors discussed earlier by:

- Limiting altitude (see Figure 3.5.4-1)
- Limiting time at altitude (see Figure 3.5.4-1)
- Limiting activity while decompressed (see Figure 3.5.4-1)
- Using preoxygenation (see Figure 3.5.4-2)

The decision to utilize measures to reduce DCS risk should be based on an accurate prediction of the risk during a planned operational scenario. Previously, such predictions were possible only when research findings were available that corresponded closely to the scenario in question. Such cases were very rare. A better method of prediction was needed.

3.5.7. Prediction of DCS

Many attempts have been made to model DCS, whether based on hyperbaric or hypobaric exposures. Commercial success with diving computers was achieved with equations that calculated the level of nitrogen absorbed from increased partial pressure of nitrogen in the breathing gas over time. The same approach has been attempted for modeling altitude exposures with some success.

An early attempt related the partial pressure of nitrogen in the tissue before decompression (PN_2) to the total barometric pressure after decompression (PB) as a ratio. It is referred to here as the tissue ratio (TR). This model results in a metric for level of supersaturation during zero-prebreathe exposures and has been used as a guide for NASA operations in space (Conkin et al., 1987) and in planning for Moon/Mars exploration) (Lange et al., 2005).

$$TR = \frac{PN_2}{PB}$$

As an example, an ascent to 18,000 ft would yield 569/380 = 1.5, which is considered quite safe based on USAF studies from the early 1980s to 2002 (Webb et al., 2003).

Although Table 2.1.2-1 shows the atmosphere of Earth as having 593.4 mmHg at a sea level partial pressure of N_2, the value of 569 mmHg of N_2 is derived by subtracting the alveolar partial pressures of O_2, H_2O, and CO_2 (Appendix 1) from the sea level total pressure (760 – 104 – 47 – 40 = 569)[1].

Unfortunately, the TR equation only describes the supersaturation present at the beginning of an exposure and does not describe the risk at any other point during the

[1] $PN_2 = PB - PAO_2 - PH_2O - PACO_2$

exposure. The added and important factor of prebreathe time complicates the equation as does activity level while decompressed. Therefore, it is of no practical use in the USAF environment and is only mentioned for background.

The need for a much better model was addressed by Pilmanis et al. (2004) following development and validation with human trials. It is the only altitude DCS model tested using accepted validation procedures. Before this model was developed, estimates of DCS risk were based on research chamber exposure scenarios, which were likely to be quite different from the planned operational exposures. The development of the model included a mathematical model of bubble formation and growth together with a log-logistic statistical model using the extensive Air Force Research Laboratory (AFRL) Altitude DCS Research Database (Kannan et al., 1998). The model is called the Altitude DCS Risk Assessment Computer (ADRAC) model. It is available via the AFRL web site (Internet Resources, see Appendix 8).

3.5.8. DCS Incidence: Research vs. Operational

As long as there are missions that require airmen to transit the atmosphere at altitudes that may induce decompression sickness, there will be a need to understand and apply research in high-altitude physiology (see Webb, 2010a&b). Translating research results to operational DCS risk has consistently resulted in some confusion. The research community routinely reports a much higher DCS risk than operational reports of DCS or DCS-related mission aborts indicate is present. Figure 3.5.8-1 depicts how the high incidence of DCS observed during research exposure to the U-2 cockpit environment simulating a high-altitude reconnaissance mission actually translates to few operational reports or aborts. In this hypothetical example, each step, from research subject exposures performing mild exercise including walking to resting pilots with high incentive to complete a mission, involves halving the incidence. Note: The graph is a possible explanation to the disparity between research and operational DCS risk. It has not been tested and is the author's "best guess" as to the causes of the differences.

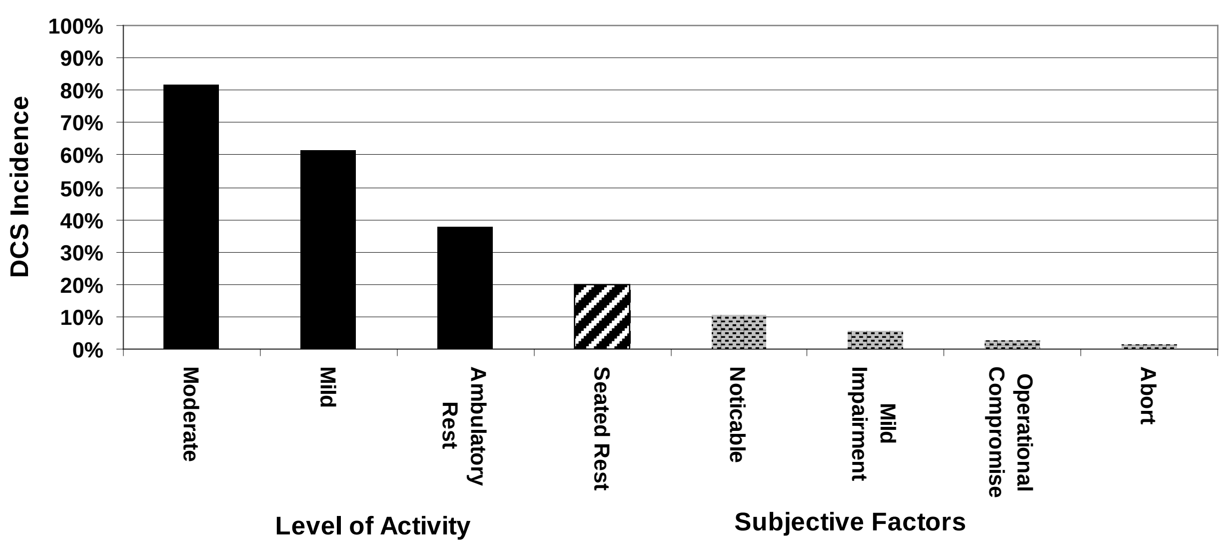

Figure 3.5.8-1. Hypothetical Explanation of the Difference Between Research Results and Operational Risk of DCS During a 4-hr Exposure to 30,000 ft with a 1-hr Prebreathe

Research Results with Moderate Exercise. Human volunteers are directed to report even the slightest change in well-being during the exposure, and this results in about 80% DCS reported by subjects in Brooks studies under the conditions described in Figure 3.5.8-1. Report of even very mild symptoms is necessary to protect research subjects from more serious symptoms that could occur with continued exposure. ***Research Results with Mild Exercise*** shows a reduction in DCS incidence consistent with a reduced level of effort. ***Research Results with* Ambulatory Rest**, merely walking a few steps every 10-20 min, produced even less DCS (Webb et al., 2010a; also see Figure 3.5.4-3). ***Research Results with* Seated Rest** is what pilots do during cruising flight, albeit including some arm movement, which only uses two-thirds as much energy as slow walking. This activity is estimated to yield about 20% DCS (hashed bar) based on a report in peer review (Webb et al., 2010a) that shows a linear relationship between DCS incidence and the highest 1 min of oxygen consumption during a 15- to 20-min sequence of activity tested.

The next descriptions are a theoretical explanation of the differences between existing research findings and operationally reported DCS. Probably only about half of the symptoms reported by resting research subjects would be ***Noticeable*** by operational crew doing their jobs. Thus, only about 8% of operational missions may involve any noticeable DCS and even then a perception that they are not important or not DCS may prevail. Only about half of the noticeable symptoms would likely involve ***Mild Impairment*** of operational function. Perhaps only about half of those would be severe enough to result in an ***Operational Function Compromised*** situation. Although that 2% symptom incidence should be reported, the high level of mission orientation may yield a lower number, especially since the symptoms would usually disappear during descent. Probably only about half of those symptoms that should be reported actually result in an ***Abort*** by a mission-oriented crewmember reluctant to do so (Bendrick et al., 1996), affecting probably less than 2% of the missions. Included here are the aspects of peer pressure, inconvenience of treatment, and even career protection. Additional prebreathe or use of exercise during prebreathe (Webb et al., 1996, 2010b; Hankins et al., 2000) by susceptible individuals may reduce the abort risk to less than 1%.

3.5.9. Summary

The research done on altitude DCS during WWII and in the early years of the space program provided answers and raised questions that were addressed from the 1980s to 2005 by research at USAFSAM and AFRL facilities at Brooks AFB (City-Base). Many of those findings are referenced here to provide further resources. Production of the first altitude DCS risk assessment computer model during that period represents a large advance in the capability to predict DCS risk under many conditions. Although rare in current aircraft operations, the potential for DCS to interfere with optimal human performance remains significant. It is incumbent on aerospace physiologists to use the knowledge gained in the past 60+ years to prevent DCS from being a limiting factor in future aerospace applications.

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Concepts

- Altitude vs. diving DCS
- Decompression sickness (DCS)
- Four categories of DCS symptoms
  - Limb pain
  - Skin
  - Neurologic
  - Respiratory
- Four primary factors that affect DCS incidence
- Standard of DCS care

Vocabulary

- Body mass index (BMI)
- Break in prebreathe
- Exercise during prebreathe
- Hyperbaric oxygen (HBO) therapy
- In-flight denitrogenation
- Maximal oxygen uptake
- Prebreathe, preoxygenation
- Rate of ascent
- Repeated exposure
- Sigmoidal relationship
- Venous gas emboli (VGE)

4. HUMAN PERFORMANCE EFFECTS

4.1. Human Performance Optimization

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4.1.1. Human Factors in Aviation

"A classic tale of Human Factors: Icarus, the son of Daedalus was imprisoned in the Labyrinth on Crete to punish Daedalus for helping Theseus to kill the monster called the Minotaur and to escape with King Minos' daughter, Ariadne. Daedalus knew that Minos controlled any escape routes by land or sea, but Minos could not prevent an escape by flight. So Daedalus used his skills to build wings for himself and Icarus. He used wax and string to fasten feathers to reeds of varying lengths to imitate the curves of birds' wings.

"When their wings were ready, Daedalus warned Icarus to fly at medium altitude. If he flew too high, the sun could melt the wax of his wings, and the sea could dampen the feathers if he flew too low.

"Once airborne, Icarus became exhilarated by flight and ignoring his father's warning, he flew higher and higher. The sun melted the wax holding his wings together, and the boy fell into the water and drowned. Daedalus looked down to see feathers floating in the waves, and realized what had happened. He buried his son on an island which would be called Icaria, and the sea into which Icarus had fallen would ever after be called the Icarian Sea." (Thompson, 1999)

Over the century since manned flight began in earnest, great progress has been made in both the engineering and human integration of man-to-machine systems. The earliest investigations of the tragic loss of life and materials were often centered on engineering aspects of flight or operations. Once the reliability of the machine is confirmed, many investigators still fall short of dealing with human performance issues. The study of human factors causes the reader to pry deeper into the interaction of the operator with the machine. Most accident investigation teams have precise engineering perceptual frameworks and are more comfortable working with data, yet many human factors elements are linked to circumstantial evidence that cannot be duplicated in a laboratory.

The Royal Flying Corps (UK) was the first to harness human factor specialists in the form of flight surgeons during the First World War. The aeromedical factors identified during the early investigations have become foundational to our current human factors rubric. As manned flight expanded from military to commercial aviation, human factors became a greater concern. Materials continue to improve, but the human retains weak points that are often the source of error.

To fully embrace human factors as a profession or function of safety, one must approach the field with a systematic progression. The process begins with descriptive survey and observational methods (What did you see?), to controlled laboratory experiments (Can we replicate behavior in a simulator?), and back to a field experiment to validate the findings. Human factors (HF) is an applied science, and as such, the

practitioner must use scientific reasoning to guide the activities of any investigation. The same scientific method used in a chemistry lab is used in the HF field; continuous refinement and development of theory based on observations is critical to satisfactory outcome.

Identification, classification, and analysis of human error is the cornerstone of reliability and human error in complex systems. Errors are typically linked to inadequacies of system design and are grouped into three categories (Proctor, 1994). The first is linked to task complexity: the limitation of the human to process information or the capacity to recall, calculate, or attend to information presented from the system. The second is linked to error-likely situations: the predisposition of the operator to making an error due to inadequate training, procedures, or poor supervision. The third category is linked to individual differences: the susceptibility to stress, inexperience, and attitudes can produce as much as a tenfold increase in human error probability. For example, the closest relationship with overall number of errors made on a flight deck was found in the communication category “acknowledgement”: the acknowledgement of one crew member that a piece of information has been received is a critical part of the feedback loop. Reinforcement of communication between two or more crew members reflects that a harmonious flight deck atmosphere is less likely to produce errors than a tense, strained one (O’Hare, 1990). Most recently, the flight deck has expanded to an ever-broadened geography including the mission control element, the sensor operator, the battlefield commander, and other aerial weapons systems all working in unison to achieve a singular mission objective. Data that support the case for human factors must be grounded on solid scientific method, as this study demonstrated through the use of cockpit voice transcripts, simulator reenactments, and role play with aircrew followed by observation on a flight deck. Analysis of 4,000 mishaps linked to pilot-causal factors converged on a single conclusion about human performance: judgment errors (e.g., decision-making, goal-setting, and strategy-selection errors) were associated with major accidents whereas procedural and response execution errors were linked to minor accidents (Wiegmann & Shappell, 1997). One challenge of the current generation of aviators is employing “air sense” without the experience of flying an aircraft. Numerous studies have attempted to pin down the importance of experience in decision-making and skill-based activities. Expert pilots are likely to use flexible task management during emergencies and procedural task management during routine flying (Kennedy, 2010). Often, novice pilots are not aware of the decisions to be made and may struggle sorting information that is “important and relevant.” The challenge of remotely piloted vehicles may level the playing field between experienced pilots and novices when it comes to task management, as the interplay of working memory and sensory-motor input is reversed.

There is virtually no limit to the dimensions that can be captured in human factors analysis and, likewise, no limit to the fields that HF can be applied. Human physiology can be a useful link to understanding the human interface within a system. Color perception, auditory cues, sensory stimulation, neurological limitations, and even basic strength and endurance can each have a role in understanding why errors occur and how to develop methods to mitigate errors. For example, when evaluating color cue on displays, it is important to note that the effect of color on task performance is very situation specific. A number of considerations may influence the effectiveness of multifunctional displays. Color coding on a multifunction display must account for symbol density (number of symbols displayed), discrimination of color (contrast and redundancy), viewing time (dependent on other tasks and location of display), and skill

level of user (Weiner, 1988). Additionally, there are cultural cues that are relevant to understanding response and interpretation of colors and symbols on a display. The linkage between physiology, psychology, and operational experience (e.g., training) is evident in this example.

The fundamental processes involved with operating complex systems have changed widely over the first century of manned flight. Classic human factors models lined up useful but disparate processes in an attempt to explain error. Bainbridge describes the five main cognitive functions involved in a human-machine interface: discriminating a stimulus, perceiving whole parts of sensory input, naming the input, choosing an action, and comparison across a range of processes (Garland, 1999). From this, it is clear that no human response is made in isolation. The influence of the environment and individual capacity and experience are at the bedrock of our role as human factors practitioners.

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4.1.2. Human Factors Training

"Human factors is that branch of science and technology that includes what is known and theorized about human behavioral and biological characteristics that can be validly applied to the specification, design, evaluation, operation, and maintenance of products and systems to enhance safe, effective, and satisfying use by individuals, groups, and organizations" (Christensen et al., 1988).

Our little knowledge of human beings has been gleaned at a person-to-person level and by day-to-day contact with working associates in aviation. Much was learned over the years by observing and talking to other more experienced instructors of aviation and science, both good and bad. If good tutors in human factors awareness had been available 100 years ago, would we be facing the same struggle with the man-machine interface as the 21st century human factors expert? It is rare indeed to find teachers addressing this subject in formal class anywhere, when secondary education ignores it as a subject to be taught. Flying training organizations do try harder to promote human factors awareness in instructors, beyond the content of student pilot multicrew cooperation or crew resource management (CRM) courses. Notwithstanding, aerospace physiology instructors usually need to find out and learn "the hard way" about human factors and reactions in the operational environment, not leaving behind the lessons found in text books but building on the theoretical to the practical application. Where does one then learn about human factors? The dearth of human factors information and guidance has prompted much work since 1985 to fill a glaring gap on the subject. Training in the field of HF covers a broad variety of specialty areas, from ergonomics and anthropometry, engineering and design, cognitive psychology and

physiological response to the environment. The HF specialist uses scientific processes to analyze the human component as a subsystem of the whole operation. As early as the 19th century, researchers have been studying the interaction between man and machine. Ernst Weber established a quantitative measure, now known as Weber's Law, that made possible the expression of one's ability to tell that two stimuli differ in magnitude. Weber's Law is expressed as:

$$\Delta I / I = K$$

where Δ = change, I = the intensity of a stimulus, I = the amount of change between it and another stimulus needed to tell that the two stimuli differ in magnitude, and K is a constant (Weber, 1978).

Applied in the aviation environment, the designer of warning signals might consider the intensity of a warning light against all lighting conditions in a cockpit to ensure the difference between signals is identified by the operator. Or, similarly, a warning tone must be presented against the other environmental noise to ensure the tone is heard.

In aviation physiology, aircrews are taught new skills based on both motor theory and cognitive theory. Neuromuscular patterns of activity are established during physical practice of tasks, like selecting regulator settings during hypoxia recovery. Secondly, mental practice allows the individual to establish a mapping sequence of action before actual physical practice begins. The cognitive components of a task that are rehearsed apparently reinforce the physical components of a practiced task. Unfortunately, training environments are not often identical to the operational environment, and this may lead to a problem of transferring skills from one to the other. Any form of training – simulators, emergency procedures, equipment operation – should aim to produce positive transfer. Negative transfer is the result of a previously learned stimulus-response reaction being reassigned so that stimuli that require one response now require another. For instance, if controls or displays are reversed, or control switches are configured differently, the likelihood of negative transfer is higher. When developing demonstrations in aerospace physiology, it is critical to consider the operational environment and match the training materials and devices as closely to the flight environment as possible. One limiting factor is the broad population serviced in aerospace physiology. When discussing and practicing oxygen discipline, for example, one objective is to establish aircrew confidence and competency in the use of oxygen equipment. This is complicated when neither the oxygen equipment nor the environment it is employed in aerospace physiology matches the operational equipment, e.g., joint helmet-mounted cueing system (JHMCS) and environment the aircrew will face outside of training (Fig. 4.1.2-1). The concepts of education and training are pivotal in development of human-factors-based curricula.

Education and training are actually two distinct aspects of the instructional process. Education is most associated with broad-based sets of knowledge, values, attitudes, and skills. The concepts presented under the banner of education are foundation stones for the aircrews to build specific job skills upon. Training, on the other hand, is aimed at developing specific skills, knowledge, or attitudes. The skills developed during instruction can be organic, as in language-based, physical, intellectual, or social. The objective measure of success in human factors training must include acquisition of both the knowledge (education) and the skill (training) to use the information.

Figure 4.1.2-1. JHMCS Helmet

Review of hundreds of accident reports reveals that, while human error, particularly operator error, is the most frequently cited causative factor, it is so often contaminated by other errors and events that the magnitude of its contribution may be less than publicized. If errors of intent were personal choice, that is, they involved a known violation, the analysis of human factors could be considered in terms of whether the act is the normal approach of the individual based on competence, attitude, or ignorance or an unusual circumstance that involved no apparent background cause. Human factors taxonomies are clear to point out that few errors can be ascribed to the individual alone without other personnel or material involvement. So the human factors practitioner preparing to teach a lesson in error mitigation must consider selecting examples that point out errors of intent committed for no apparent reason as well as errors not by intent, committed with no extenuating circumstances. An example of the first might be low flying a residential area by a trained, competent, experienced pilot who is well aware of the hazards; essentially a premeditated violation of flight rules. An example of the second might be a gear-up landing by a pilot of comparable training, experience, and ability that occurred under optimal conditions with no extenuating circumstances and that the pilot did not recognize or accept even after the aircraft scraped to a halt on the runway. The inadvertent actions of omission or commission that lead to this second kind of error defy evaluation except in terms of dynamic psychoanalytical concepts. It is only human factors accidents caused by these kinds of error that might be considered pure or uncontaminated operator-error events. Short of recording every action of the aircrew in flight and reviewing the actions following each mission, the errors committed are often uncorrected.

In order to best address the concept of human factors, it is helpful to start with a definition. The framework of an effective definition must be founded on performance factors related to humans, and it must be crafted for specific environmental challenges. Understanding where the performance breakdowns occur further amplifies the character of errors and may lead to performance improvements. Human factors must be approached as a multidisciplinary activity.   Professor Edwards declares that "Human Factors is concerned to optimize the relationship between people and their activities, by the systematic application of human sciences, integrated within the framework of systems engineering" (Civil Aviation Authority).

The best way to illustrate the importance of studying human factors is through examples of air disasters.

- In 1977, two B-747s collided while on the runway at Tenerife, with a loss of 585 passengers and crew. A breakdown in normal communication procedures and misinterpretation of verbal messages were considered factors (ICAO Circular 153-AN/98) (Fig. 4.1.2-2).
    - A series of three B-737s crashed due to "rudder-over" conditions, uncommanded rudder deflection causing loss of control and impact with the ground. A good example of human factor failures may exist amidst a flawed design in a single model within two different airlines; nothing changes over a period of years until another failure triggers a design review.
- In 1987, an MD-80 crashed on take-off in Detroit. The pilots had not set the flaps, thus violating standard operating procedures. Also, the take-off configuration warning did not sound, for undetermined reasons (NTSB/AAR 88-05) (Fig. 4.1.2-2).

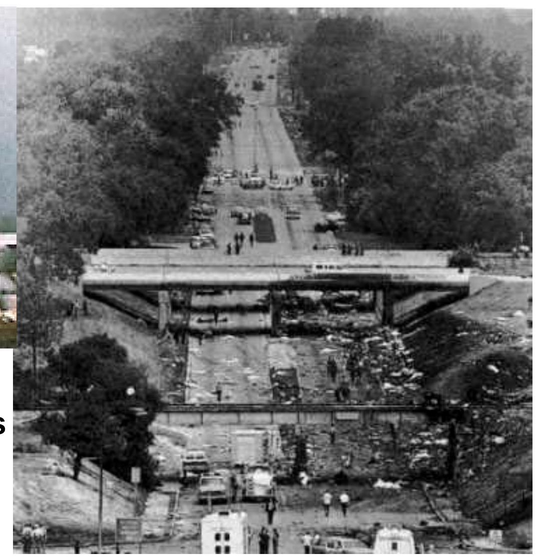

Figure 4.1.2-2. Tenerife and Detroit Accidents

Human factors experts can assist in the analysis of accident investigation findings and often contribute to recommendations of remedies. In the context of human factors design-induced errors, procedural flaws, or inadequate warnings or training, the interest in understanding the linkage between the human and the system has heightened the need to refine the education and focus of today's human factors experts. According to some, forensic human factors has been part of investigations since the first aviation fatality, Lt Thomas Selfridge, a U.S. Army pilot killed after crashing a Wright Flyer in the early days of aviation. The analysis led to the search for better crashworthiness and survivability, such as the routine wear of helmets and restraints (Gilson, 1999). Nearly every manufacturing specialty uses human factors techniques to review safety and operating procedures. The cost of evaluating system safety has been a tough sell until recently. Mega-volume production of automobiles, for instance, has resulted in teams of human factors experts assigned to production staff. Many of the techniques used in the early days of HF analysis have been replaced by computer modeling such as finite element modeling for injury analysis. Additionally, the use of simulations has been commonplace in aviation for decades.

Simulation has grown to be a method used to increase exposure to tactile and procedures training. Human factors simulation is not limited to aviation. The most notable is the inclusion of simulations in the medical field. Not unlike a pilot practicing an approach to an unfamiliar airfield, HF engineers and medical experts have devised methods of modeling medical techniques using highly sophisticated tools. Clearly, the more a technique can be minimized, the better off the patient may be in recovery. The main advantage of minimal invasive surgery is to avoid the trauma linked to the opening of the patient's body. In the case of laparoscopy, a video camera and few surgical instruments are introduced inside the abdomen through small openings. This technique has the advantage of being less invasive and, therefore, shortens the stay of the patient at the hospital. However, minimal invasive surgery requires specific training due to the difficulty of moving a three-dimensional tool by looking at a two-dimensional video image, which creates a problem of hand/eye coordination. Furthermore, the manual dexterity is strongly reduced due to the shape of surgical instruments. A recent model developed by the Institut de Recherche contre le Cancer de l'Appareil Digestif (Delingette and Avache, 2005) is to provide computer software allowing:

- The teaching of the liver anatomy from three-dimensional computer-generated images
- The gesture training of a surgeon by simulating the interaction of various surgical tools with the organs of the abdomen
- The planning of the resection of hepatic segments from the computed tomography scan images of a patient

There are several advantages of a computer-aided simulator over current training techniques (mechanical simulator, training on cadavers or animals). Such a simulator would give an objective evaluation of a surgeon's dexterity combined with a more intensive training activity (Fig. 4.1.2-3). It would allow the simulation of rare pathological cases and could simulate the interaction with several organs. HF plays a major part in the refinement of equipment and software development.

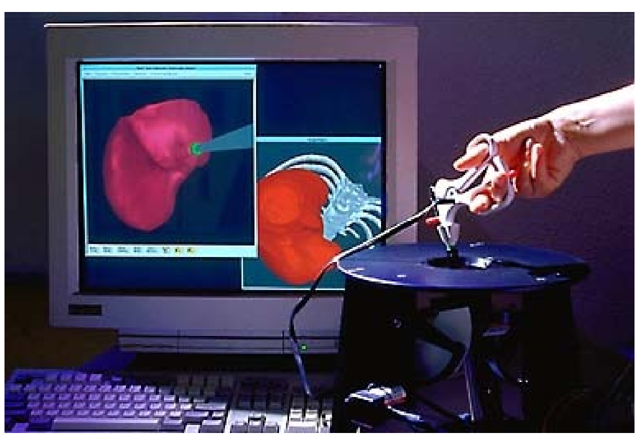

Figure 4.1.2-3. Surgical Simulation Provides Highly Realistic Training

Simulation adds value and reduces cost, but the key to efficiency lies within the transfer of skills. Are the skills and knowledge acquired in simulations of value to

actually handling an aircraft or other technical equipment? Roscoe and Williges (1980) developed the transfer effectiveness ration (TER) in an attempt to quantify the answer to this question. The ratios were defined for pilot training in the following way:

$$TER = A_c – A_s / S$$

Where TER = transfer effectiveness ratio; A_c = aircraft time required to reach criterion performance, without access to simulation; A_s = aircraft time required to reach criterion performance, with access to simulation; and S = simulator time

As Roscoe and Williges (1980) indicated, the TER is the ratio of aircraft time savings to the expenditure of simulator time; it reveals how much aircraft time is saved for every unit of simulator time invested. Positive transfer from simulators is reliant upon environmental realism and solid instruction. Simulation has consistently shown an increase in effectiveness and a reduction in costs for many aspects of flight training. Coupled with actual flight, the transfer from simulator training was almost always superior to simulator-only training (Hayes, 1992). Moreover, self-paced simulator training is superior to lock-step instruction. Once simulator work is complete, the HF instruction continues in the aircraft (Fig. 4.1.2-4).

Figure 4.1.2-4. C-17 Simulator (NASA photo EC04-0288-4, 4 Mar 1988) and C-17 Cockpit

How can the actions of an aircrew be evaluated outside the cockpit task training in the squadron? Monitoring in-flight activities may be an effective way to replay the mission as part of a training program. Mishap footage is common in classroom presentations to highlight the outcome of a mission that resulted in an accident. Typically, that footage is from an external camera, head-up display with an outside view of the flight or computer-generated images based on flight data recorded. Embedded training or testing is a concept familiar to any pilot who has reviewed gun camera footage following a mission. Flight recordings used for pilot performance assessment could be used for human factors analysis on ground-based display devices, permitting operational skills to be evaluated following actual or simulated missions. In aerospace physiology, when a video of aircrew or aircraft performance is selected for a training segment, the instructor must be thoroughly familiar with the circumstances of the mission. Developing training programs that address situational awareness, sociopsychological, and other human factors that influence aircrew performance requires comprehensive study of error, causes of error, and methods of reducing incidence or severity of human error in complex systems.

How can we keep human factors pertinent to training? Many aircrew only have a limited understanding of human factors and cockpit or crew resource management. The meanings are not explicit in the words used as a panacea for failures in human intercommunication skills. Is there a need for new terms to describe what is really intended by human factors, as applied to the various aspects of the aviation scene? The International Civil Aviation Organization (ICAO) has produced some documentation in the form of digests on the subject of human factors concepts including some material relevant to training and evaluation and also on selection processes that could be of help in general terms. CRM and line-oriented flight training concepts were also addressed in one of the early ICAO digests and could be useful to new and not-so-new aerospace physiology instructors. In the current status of HF instruction, there still seems to be a certain lack of comprehensive "human factors" material that addresses the evaluation function and the interrelationship between aircrew and other elements of the flight environment. It is recognized that, to an extent, formal training in human factors matters is better served through university instruction and supplemented by technical experience in the field. Much has been written on the subject by specialists at large and by regulatory authorities such as the Federal Aviation Administration (FAA) and universities with expertise in the study of human performance. It is imperative that all practitioners of aerospace physiology increase individual knowledge and practical application of human factors in all aspects of the human performance arena.

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4.2. Human Performance Optimization

4.2.1. Aviation Psychology and the Stresses of Flight

Lt Col Andrew W. Woodrow, USAF, BSC and David R. Jones, MD, MPH

As we consider the psychological stressors of flight, we need to keep one fact clearly in mind. *Men and women who enter aviation as a career or an avocation bring to the arena of the air all the strengths and frailties of the human race, all the varied elements of heredity, nature, nurture and experience that form our separate strengths and vulnerabilities*. Flight, with its many joys, dangers, rewards, and demands upon body, mind and spirit, can but add to the inevitable life experiences, good and bad, that the years bring to each of us (Jones, 1986).

Just as a good flight surgeon must first be and continue to be a good physician, so all those contemplating excellence in the support of the mental health, resilience, and effectiveness of a flyer in the realms of human factors and safety must first be and continue to be accomplished and able in their respective professions. Thus qualified, we may care for all aspects of the health of aviators as they proceed through their lives and careers. We can expect no less of ourselves than we do of the flyers.

4.2.1.1 Sources of Stress. The flight environment introduces physiological stress—heat, cold, noise, vibration, circadian and dietary disruptions, g-forces, multitasking workloads, sleep deprivation, cramped cockpits, and many others. Flight also introduces psychological stressors that affect effective performance and flight safety. Experiments in flight simulators that measure the time to respond to signals presented under various conditions (e.g., heat, noise, workload, etc.) have demonstrated degraded performance. For obvious reasons, a crew would not be exposed to real hazards for the purpose of measuring responses; however, accident investigations and anonymous aviation safety reports reveal a consistent downward trend in performance when facing danger or uncommon stress in flight.

A stressor is any event or situation that is perceived by an individual or group as a threat that leads either to adaptation or initiation of a stress response. Simply said, a stressor is a stimulus—the cause—and stress is a response—the effect. In aviation, the mere activity of achieving takeoff speed and configuring the aircraft for flight is stressful due to the time compression and minimal response sets available once one passes the decision speed for takeoff: continue or abort?

Dr. Hans Selye, one of the first to study the effects of stress, coined the term "eustress" to explain the positive, desirable stressors that keep life interesting and help to motivate and inspire. Events such as going to college, getting married, starting a new job, or becoming a parent can be happy, joyous, stress-producing occasions. Eustress also involves successfully managing stress even if one is dealing with a negative stressor. Eustress implies that a certain amount of stress is beneficial and, in fact, necessary to maintain overall health and performance.

"Distress" typically refers to the negative effects of stressors that drain us of energy and may individually or collectively surpass our capacity to cope. In the aviation environment, this can be linked to acute (short-term) stressors or extended stressful conditions (long deployments or other adverse life situations). Very often when we speak of stress, we are referring to distress. For the purposes of this chapter, however, we shall consider stress in relation to its effects on performance.

Humans register stress in several ways. Biometric instruments are routinely used to identify changes in heart rate, respiratory rate, sweat rate, and even pupil size. Unlike these biometric measures, hormone levels seem to differentiate levels of stress even among highly experienced aircrew (O'Hare, 1990). In one study of U.S. Air Force instructor pilots and students, urine samples were taken before and after training flights for 4 mo. Neurotransmitter levels taken after flights classified as either emergency or precautionary showed a marked increase in both instructors and students (Krahenbuhl, 1985). As a practical measure, stress hormones may not be first on the list of markers to use in a flying squadron; however, behavior and performance (outcome) are well accepted and can be graphed out for analysis.

Most readers of psychology are familiar with the Yerkes-Dodson Law (Fig. 4.2.1-1; based on Proctor & Zandt, 1994, Fig. 9-9) depicting the relation between arousal and level of performance. It is well accepted that performance reaches a peak when a certain level of stress is included with the task. The height of this peak depends upon whether the task is complex or simple. For example, a pilot flying a holding pattern in severe weather is likely to have a higher optimum level of arousal than when the same pilot is leveled out and simply checking the cockpit before a routine landing.

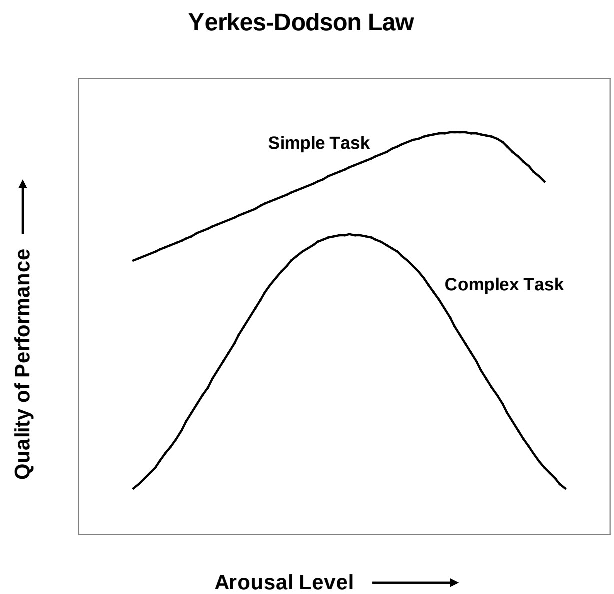

Figure 4.2.1-1. Yerkes-Dodson Law (Yerkes & Dodson, 1908)

Physiological Stress. The link between the physiological condition and the stress performance curve is important to consider. For instance, it is believed that if a crewmember is fatigued and experiencing low blood sugar, the effect of stress on performance will be greater than in a fit, rested person. The nature of our human condition is to cope or adapt to the environment; autonomic adjustments allow for adjustments to physical stress, but adaptation to psychological stress is much less pronounced and harder to measure. Despite the reasonable ease of measuring heart rate in flight and the natural correlation between heart rate and situational arousal, it is important to consider concomitant factors such as workload (physical and mental) as well as responsibility on the flight deck when assessing the overall effects of stress on performance. Considering the "whole person" of a flyer, one must also be aware of any acute or chronic life-situational stressors outside the aviation arena: those of family, career, health, finances, or legal problems, for instance.

Operational errors in day-to-day flying are the central concern for aviation physiologists or human factors experts. However, we must also consider the cumulative effects of ongoing stressors. Significant long-term health problems identified in medical records of personnel follow a career of high-stress operations, such as in air traffic control. The incidence of hypertension or elevated blood pressure in controllers has been found to be six times that of pilots (O'Hare, 1990). One question must be asked when considering stress in the workplace: "Is it the work environment, the workload, or the types of tasks that induce a stress response?"

4.2.1.2 Stress/Performance Modeling. A conceptual model has been used to explain the stress/performance relationship (Driskell & Salas, 1991). Their model considers four elements:

- The presence of a specific stimulus (warning light, alarm buzzer)
- Appraisal of the stimulus (how the individual or team evaluates the threat, situation, and resources)
- Development of performance expectations (often built through simulation/training)
- Psychological/behavioral/physiological effects

Driskell and Salas identified that the effects of stress on performance are mediated by the type of task and the severity of the stress. As an example, the perspective of an emergency break-away during aerial refueling has a different connotation from the perspective of the boom operators than the pilot in the receiver aircraft. Both have a critical task to complete: one is relying on the uploading fuel to continue the flight and safely return to home base, while the other may be in the middle of a long line of receivers and more concerned about damaging the boom, resulting in an aborted mission. Complete understanding of the stress/performance relationship must consider both chronic and acute stress, as well as the action of the entire crew and not simply individual performance. The theoretical models developed to address the stress/performance relationship cannot be universally applied without a thorough knowledge of the mission and crew composition.

Confounding the understanding of stress in the individual pilot is the general lack of understanding of the processes that a group or team (e.g., a cockpit flight crew) goes through to accomplish tasks during a mission. Group dynamics during a task-intensive scenario may be more relevant to errors than individual proficiency. In several key studies presented in realistic simulator environments, the subordinate team member often yielded to authoritative members of the team when under stress (Foushee & Helmreich, 1988). This is especially troubling if the junior member has a more complete picture of the situation but is unwilling or unable to share his/her situational awareness with the captain or other senior members of the crew.

Overcoming stress in the workplace is not as simple as removing the "offending part." Operational conditions and environments are not easily reengineered; however, one remedy for stress that affects performance is to redesign the task or its cockpit presentation. Automation has reduced the workload for many in the aviation environment, including aircrew and air traffic controllers. The introduction of glass (computerized) cockpits in the later part of the 20th century has reduced some workloads and provided a more effective suite of information displays for the operator.

Stress cannot be engineered completely out of the system, so a second consideration is the selection of personnel for positions prone to stress. Military selection processes take place before potential flyers, air traffic controllers, and other flight-essential personnel enter active flight operations. These selection sites are few (e.g., the Air Force Academy, certain training bases, NASA-Johnson Space Center), so only a few mental health practitioners are likely to become involved in this process. Briefly, the Air Force “selects-out” those considered unfit for such training due to clinical or personality-related issues. Some “select-in” considerations apply to particularly demanding mission requirements in which personnel must not only be *fully* qualified but the *best* qualified (e.g., special operations, USAF astronaut candidates). These criteria involve matters of motivation (both emotional and rational), ability (physical, cognitive, autonomic, neuropsychological, and physiological), and stability (personality, temperament, interpersonal relations). Such matters may be approached both scientifically and intuitively and form an integral part of the mental health of aviators (Jones & Marsh, 2001; Santy, 1994).

4.2.1.3 Stress Assessment and Management. There is limited knowledge of the meaning of current measures used in stress assessments. The correlations between physiological and psychological stress are not often correlated well with the broad set of circumstances a crewmember might be found in over a career. A stress performance screening test would have to account for a myriad of stressors and link to aviation-centric decision making. Developing a set of circumstances that would cover particular subject matters under varied conditions could still not reasonably capture all conditions and all candidates.

The third and most reasonable approach to stress reduction is through training. <u>Stress management</u> techniques and stress exposure interventions are the two most common methods (Johnston, 1997). Most stress management programs focus on the comfort of the individual rather than actual changes in performance. For example, in SCUBA training the trainee is inserted into a troubleshooting situation and presented a series of options to resolve the problem. In a manner similar to clinical desensitization to phobic objects through successive approximation followed by guided relaxation, this training process helps the individual become comfortable in one scenario. The student experiences a stressor and practices coping strategies under conditions of graded exposure in a controlled setting prior to confronting the actual stressful experience. This approach provides feedback and coaching while the student is adjusting his/her perception of the ability to cope with the target stressor, rather than reacting with an uncontrolled “blow-up” to the surface. The objective is to help the trainee use a particular skill set to enhance performance in the presence of a defined, predictable stressor. The combined approaches seem to be the best solution set for work in complex, dangerous environments.

Application of stress management techniques in the human factors realm is most effective when linked to performance issues. The practitioner of aviation physiology and human factors should understand the nature of the environmental stressors and the tasks of each crewmember in completing a successful mission before constructing a solution set for reducing stress. Intervention must be supported by research relevant to the environment of concern. Safe, effective human performance is the goal; stress management is the tool.

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Concepts

Stress management
Yerkes-Dodson Law
Physiological stress

Vocabulary

Stressor

4.2.2. Self-Medication

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4.2.2.1 Introduction. The ever-increasing availability of medications of all types creates an environment of risk for our aircrews. The aerospace physiologist must be knowledgeable about over-the-counter (OTC) medications approved for aircrew use, nutritional and herbal supplements, and the process for approval by the flight surgeon for usage. Lists of medications are useful, but the guiding principle for any medication usage is the potential for impairment of psychomotor function, vigilance, or disturbances of the special senses. In addition, the underlying condition for which medication is sought must be minor and not interfere with flight duties or the use of life support equipment. This chapter will review current USAF policy for OTC medication usage and issues and challenges with nutritional and herbal supplements and provide resources for future reference and study.

4.2.2.2 Current USAF Policy for OTC Medication Use in Aircrew. Table 4.2.2-1 lists OTC medications approved for occasional use by aircrew without flight surgeon approval. The condition must be minor and self-limited and not interfere with flying duties or life support equipment. Occasional use is defined as 72 hr of continuous use unless otherwise stated. Medications are listed by the generic name with examples

of trade names given in parentheses. Any questions about a medication or condition should be referred to a flight surgeon.

Table 4.2.2-1. OTC Medications Approved for Use by Aircrew without Flight Surgeon Approval

Oral Medications for Occasional Use for a Maximum of 72 hr Continuous Use	No More than 2 Doses Per Week for Heartburn Symptoms Lasting <48 hr	Topical Medications for Occasional Use (Condition Must not Interfere with Flying or Life Support Equipment)
Acetaminophen *(Tylenol)*	Famotidine *(Pepcid)*	Hemorrhoid medications *(Preparation H, Tucks)*
Ibuprofen *(Motrin, Advil)*	Omeprazole *(Prilosec)*	Topical antifungals *(Tinactin, Lotrimin)*
Aspirin	Ranitidine *(Zantac)*	1% hydrocortisone cream *(Cortaid)*
Naproxen *(Naprosyn)*		Vaginal anti-fungals *(Monistat)*
Antacids *(Mylanta, Maalox, Tums, Rolaids)*		Anti-infectives *(Polysporin, Neosporin)*
Bismuth *(Pepto-Bismol)*		Analgesics *(BenGay, IcyHot, Aspercreme)*
Fiber *(Metamucil, Fibercon)*		Benzoyl Peroxide
Simethicon *(Gas-X)*		Chlorhexidine *(Peridex)*
Docusate (*Colace)*		Salicylic Acid (warts)

Ref: Official Air Force Approved Aircrew Medications: OTC Medications Aircrew Are Allowed to Take Without Flight Surgeon Approval. Effective 31 March 2008. Available at https://kx.afms.mil/aerospacemedicine (restricted access).

4.2.2.3 Nutritional Supplements.

1. Current USAF policy on the use of nutritional supplements is found in the Surgeon General policy letter dated 28 Oct 1999. The only supplements specifically prohibited for use are anabolic steroids and hemp oil. Ephedra (Ma Huang) was removed from the market by the Federal Drug Administration (FDA) in 2004 following numerous reports of death and serious injury. Official lists of prohibited or approved nutritional supplements for aircrew use do not exist. All nutritional supplements must be reviewed and approved/disapproved by the flight surgeon and documented in the medical record. An SF600 overprint is available for this documentation (see Appendix 8: Internet Resources).
2. Evaluation of a nutritional supplement should include a review of all the ingredients, identification of intended effects, proof of efficacy, unintended side effects, potential for risk of sudden incapacitation, decrements in psychomotor functioning and higher senses, easily detectable adverse reactions, and compatibility with performance in sustained flying operations in austere environments.
3. Although there is not an official list of approved or disapproved substances, some substances are known to have effects that could adversely impact aircrew

performance. Familiarization with these substances will aid in the education of aircrew and avoidance of risk. These substances are listed in Table 4.2.2-2.

4. Risks of nutritional and herbal substances stem from the lack of regulation in this industry. Substances may not have consistent amounts of product, may not be efficacious, may contain pharmaceutical products or near relatives of pharmaceutical products, may have a narrow difference between therapeutic and toxic doses, and may contain contaminants such as heavy metals.
5. Energy drinks are a subset of nutritional supplements that should be evaluated by the flight surgeon before aircrew use. Energy drinks contain substances that range from caffeine to ephedra-like substances to psychotropic substances. Aircrew are at risk from the cumulative effects of the stimulant substances in these drinks along with other components of their diet. Aircrew should be educated on proper usage of caffeine as a counterfatigue agent and avoidance of dangerous stimulants that may be in energy drinks. The flight surgeon and physiologist should be aware of and evaluate the energy drinks available on base and in the snack lounges of the flying squadrons. Common substances in energy drinks are listed in Table 4.2.2-3.
6. The physiologist should focus on the education of aircrew about the risks and benefits of nutritional supplements and the benefits of a healthy diet, adequate sleep, and exercise.

Table 4.2.2-2. Common Nutritional Supplements of Concern for Aircrew

Substance	Common Uses	Other Information	Potential Adverse Effects
Bitter Orange *Citrus Aurantium*	Stimulant Weight loss	Substitute for Ephedra Contains synephrine	Tachycardia, hypertension, fainting, heart attack, stroke
Black Cohosh	Hot flashes, night sweats, menstrual irregularities	No evidence of effectiveness	Liver damage, headaches, stomach discomfort
Chaparral Creosote bush Greasewood	Anti-cancer Weight loss	Not considered safe	Liver damage, stimulate cancer growth, dermatitis
Comfrey Blackwort Bruisewort Slipper root	Anti-fungal (topical), Anti-inflammatory (topical), Anti-Cancer	FDA recommended removal from market in 2001. Pyrrolizidine alkaloids (main chemical) are not considered safe.	Liver damage
Ginkgo Biloba Maidenhair tree Baiguo Yinhsing	Improve memory, dementia, vascular disease, sexual dysfunction, multiple sclerosis, tinnitus, fatigue	Most rigorous studies show no effect. Uncooked seeds contain gingkotoxin.	Headache, nausea, diarrhea, seizures, dizziness, bleeding
Ginseng *Panax ginseng* Asian ginseng	Immune booster, increased stamina and performance, erectile dysfunction, hypertension, diabetes	Limited evidence of effectiveness	Hypoglycemia, headache, sleep problems and GI symptoms
Guggul	Lower cholesterol, weight loss, acne, anti-inflammatory	Clinical trials show efficacy in lowering cholesterol and weight loss.	Stimulates thyroid hormone production
Kava *Piper methysticum*	Sedative hypnotic, anxiety, insomnia	FDA warning for liver damage	Sedation, severe liver damage, dystonia
Lobelia Indian weed Pukeweed Gagroot Vomitwort Bladderpod	Smoking cessation	Lobeline is a nicotinic receptor ligand	Nausea, vomiting, dizziness
St. John's Wort *Hypericum perforatum*	Depression, anxiety, sleep disorders	Significant drug interactions	Anxiety, dry mouth, dizziness, GI symptoms, fatigue, headache, sexual dysfunction
Saw Palmetto	Benign prostatic hypertrophy, decreased sex drive, hair loss, hormone imbalance	May be effective for BPH, but waiverable medication is available.	GI symptoms
Valerian	Anxiety, insomnia	Use approved sleep aids when indicated	Sedation
Yohimbe	Sexual aid, erectile dysfunction	Alpha-2-adrenergic blocking agent	Hyper/hypotension, tachycardia, headache, dizziness, anxiety, paralysis, psychosis, seizure

Table 4.2.2-3. Substances Commonly Found in Energy Drinks

Caffeine	Stimulant; #1 ingredient
Guarana	1g = 40 mg caffeine; may contain theobromine or theophylline
Inositol	Major component of cell membranes; many advertised but unproven benefits; reported side effects include nausea, dizziness, headache
Taurine	Amino acid with insulin mimicking properties; regulates nutrient transport into the cell and may decrease muscle breakdown
Super Citramax (Hydroxy Citric Acid, Garcinia Cambogia Extract)	Acts to suppress appetite, increase fat burn, and increase serum levels of serotonin
Glucuronolactone	Metabolite of glucose metabolism in the liver; no clear benefits or side effects; levels in drinks may be excessively high
Carnitine	Amino acid important in cellular energy production; the body makes sufficient amounts; no proven benefits
Yohimbe	See Table 4.2.2-2
Panax Ginseng	See Table 4.2.2-2

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Concepts

Current USAF policy

Vocabulary

Over-the-counter (OTC) medications

4.2.3. Tobacco and Alcohol

4.2.3.1 Tobacco. Smoking tobacco has particular significance to the flyer, since there are both short- and long-term harmful effects from smoking cigarettes, cigars, and pipes. The effects have been well documented in the 2004 Surgeon General's Report on the health consequences of smoking and in sources documenting the adverse effects on aircrew performance (Bronson, 1979; Robinson & Wolfe, 1976). AFI 40-102 specifically "discourages the use of all tobacco products."

Carbon monoxide (CO) is a colorless and odorless gas produced by the incomplete combustion of organic matter. Smoke from one cigarette can contain up to 21,400 µg of CO. The CO binds to hemoglobin, displacing oxygen, to form carboxyhemoglobin. Nicotine is found in concentrations of 200 to 2,400 µg per cigarette. When you smoke, nicotine causes the heart to work harder while the carboxyhemoglobin reduces the oxygen needed by your heart to work properly (Answers4Families). Tar, the particulate matter that remains after moisture and nicotine have been removed, is the most practical single indicator of the total carcinogenic potential of tobacco smoke. The effect of CO on the human body is both cumulative and persistent. Initially, a cigarette smoker can inhale an average concentration of CO into the lungs of 400 ppm or 0.04%.

Studies of cigarette smokers in a Colorado town with an elevation of over 10,000 ft concluded that the adverse effect of cigarette smoking on oxygen transport may be especially pronounced at high altitudes and may restrict an individual's ability to adapt to reduced oxygen tension; reduced oxygen tension refers to lower partial pressure of oxygen at higher altitudes. This same effect is equally critical for smoking crewmembers who fly in pressurized aircraft at cabin altitudes between 7,000 and 8000 ft. Smoking crewmembers flying at a cabin altitude of 7,500 ft with carboxyhemoglobin (COHb) levels of 5% and 10% will have a physiological altitude of 11,500 ft and 14,000 ft, respectively. Thus, the smoking crewmember performs his/her tasks at physiological altitudes above the altitude requiring oxygen, according to AFI 11-202v3 General Flight Rules.

Continued smoking produces the COHb levels previously mentioned. Since the estimated half-life of CO in the body is 2 to 4 hr, the effect of smoking is long lasting. Some studies have shown that moderate smokers (1 to 1-1/2 packs a day) have had levels as high as 4.5% COHb in their blood after 8 to 15 hr of deprivation. Thus, a smoking crewmember inhales concentrations of CO far above the amount determined by the Air Force as a healthful atmosphere.

4.2.3.2 Alcohol. The ingestion of alcohol, liquor, wine, or beer is common in most social cultures. Ethyl alcohol is the active ingredient in these beverages and acts as an anesthetic drug, which depresses the brain. Also present are volatile substances that slow down the rate at which the body disposes of ethyl alcohol. Alcohols are poisonous to the body; ethyl alcohol is the least poisonous and most tolerated by the body.

Acute Effects of Alcohol. The intoxicating effects of alcohol are brought about in two major actions on the brain; one effect is a change in the proportion of two chemicals called neurohormones, which affect the brain. These neurohormones, serotonin and norepinephrine, are believed to control mood and alertness. After consumption of small amounts of alcohol, a crewmember may lose normal cautionary attitudes and become reckless, possibly before he/she even notes a change in skill or performance.

Another effect of alcohol is a reduction in the ability of the brain cells to utilize oxygen. Hypoxia enters the mental picture, causing judgment and performance to be impaired. Alcohol also acts as a relaxant and anesthetic, removing a person's inhibitions and lessening his/her worries. In larger amounts, this relaxation progresses to actual unconsciousness and eventually leads to death due to respiratory paralysis.

The concentration of alcohol in the blood and brain depends on three factors: the amount consumed, the rate of absorption from the stomach and small intestine, and the rate of its metabolism by the body.

The rate of absorption depends on many factors: the type and quantity of food in the stomach, the degree of hydration of the body, the concentration of alcohol in the beverage and the type of beverage with which it is mixed, how fast the alcohol Is consumed, body weight, and the individual variation in the absorptive characteristics of the stomach.

The rate of metabolism or digestion of alcohol in the body is relative constant. Two to 10% of the alcohol is excreted through the lungs and kidney and the remainder is oxidized by the liver. It takes about 1 hr to eliminate 0.33 oz (9.8 mL) of pure ethyl alcohol from the body. This is the amount of ethyl alcohol in 0.67 oz (19.6 mL) of 100-proof liquor or in 6 oz (170 mL) of beer. The metabolism of alcohol cannot be expedited by any readily available method or remedy. Walking, drinking black coffee, breathing 100% oxygen, or taking cold showers are common folklore methods that have failed to eliminate alcohol from the body.

Blood Alcohol Level (BAL). The physiological effects of alcohol depend on the level of alcohol in the blood. Several terms have been used to express BALs: milligram percent (mg%), grams alcohol per 100 milliliters whole blood (gm/100 mL), and percent of alcohol in the blood.

The use of the term "mg%" is a misnomer, since it refers to the number of milligrams alcohol in 100 mL whole blood. To convert from mg% to percentage of alcohol in the blood, one must first convert to gm/100 mL, then multiply by 100.

For example, an individual whose blood alcohol level is 200 mg% would have an alcohol level of 200 mg/100 mL whole blood or 0.2 gm/100 mL whole blood.

$$200\ \text{mg\%} = \frac{200\ \text{mg alcohol}}{100\ \text{mL whole blood}} = \frac{0.2\ \text{g alcohol}}{100\ \text{mL whole blood}}$$

Since the density of blood is approximately 1 g/mL, 100 mL blood weighs approximately 100 gm. Therefore,

$$\frac{0.2\ \text{g alcohol}}{100\ \text{g whole blood}}\ X\ 100 = 0.2\%\ \text{alcohol in the blood}$$

With 0.05% to 0.10% of alcohol in the blood, mild intoxication is present, which will lower altitude tolerance even if symptoms are not observed. With 0.10% to 0.15% alcohol in the blood, everyone is affected to some degree. In most states, an automobile driver with this level would be considered intoxicated. At a blood alcohol level of 0.15% to 0.20%, performance deteriorates and there are marked symptoms. At 0.30%, acute intoxication and lack of coordination occur, and consciousness is lost.

Unconsciousness and possible death may result at levels of 0.40% to 0.50%. For an average 160-lb (72.6-kg) man, 2 oz (58.8 mL) of 100-proof whiskey consumed in 1 hr will produce 0.05% in the blood. If a person weighing 160 lb (72.6 kg) were to

consume approximately four-fifths of a quart of whiskey in 1 hr, it would be fatal. Since the effects of alcohol are compounded by altitude, 10,000 ft (3,048 m) of altitude doubles the effects of alcohol on the body.

Chronic Effects and Hangover. Of the many chronic effects of alcohol, those usually having long-term effects on health are found in people suffering from alcoholism. Chronic effects such as vitamin, mineral, and protein deficiency and a fatty liver are caused by improper diet and the direct effect of alcohol. Excess of body carbohydrates, cirrhosis of the liver, and alcoholic psychosis are other effects the heavy drinker may suffer.

The effect of a hangover probably constitutes a more significant flight safety hazard than does the mild intoxication state of alcohol ingestion. It is unlikely that an Air Force flyer would attempt to fly an aircraft while intoxicated. However, the same flyer 8 to 18 hr later, with a hangover, may not abort a flight although he/she is less efficient and less physically capable than normal.

The symptoms of a hangover are not entirely due to alcohol ingestion. Many are due to the activities that often accompany overindulgence in alcohol: excessive tobacco smoking, loss of sleep, improper diet, etc. Alcohol is a known cause of dehydration, resulting in many of the hangover symptoms. Alcohol takes moisture from the cerebral spinal fluid that surrounds the brain. Loss of fluid causes tension on the supporting structure of the brain, producing a headache. Dehydration can be increased by exposure to low atmospheric pressures, breathing dry oxygen, and thermal stress. In the early stages of dehydration, judgment and emotional changes are observed, and each can seriously interfere with the flyer's ability to carry out tasks safely and efficiently.

Alcohol also causes disorientation because of its combined effect on the lower brain and inner ear. The effect on the inner ear may be identified by involuntary reflex eye muscle movement 36 to 48 hr after heavy drinking. Holloway (1994) reviewed 155 empirical studies from 1985 to mid-1993 and concluded: ...that since alcohol sensitivity can vary from time to time, person to person, and situation to situation, the setting of a "safe blood alcohol content will always be arbitrary, being based on a low, but non-zero, incidence of effects below that level." Campbell & Bagshaw (2002) indicated 0.03% BAL "...increases the likelihood of an individual having any form of accident." They also pointed out that impairment of judgment could be measured at 0.05% BAL and that loss of performance could occur after only one drink and by the products of alcohol metabolism.

Time is the only factor that will alleviate a hangover. Other symptomatic relief can come from eating a well- balanced meal, which provides nonalcoholic carbohydrates to the liver, and by consuming large quantities of nonalcoholic fluids to reduce dehydration. Breathing 100% oxygen has no direct effect on a hangover.

The way to avoid flight safety problems resulting from a hangover is to educate the flyer to the hazard that persists for many hours after alcohol ingestion. There is no objective test to measure the effects of a hangover. The effects on the eye, inner ear, fluid balance, etc. require many hours of "bottle to throttle" separation for truly safe flight conditions to exist. The old adage about "an ounce of prevention is worth a pound of cure" is especially true in the three-dimensional world of extra stresses in aviation. The person affected may determine overt symptoms are gone, but one of the most dangerous aspects of this problem is determining when and where the physiological compromise stops so that safe flight can be accomplished.

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Concepts

2004 Surgeon General's Report

Vocabulary

Carbon monoxide (CO)
Carboxy-hemoglobin (COHb)
Blood alcohol level (BAL)

4.3. Fatigue and Fatigue Countermeasures

James C. Miller, Ph.D., CPE

4.3.1. Human Fatigue and its Effects

In any human-machine system, including weapons systems, the most unpredictable component in the system is the human. After training and currency, the greatest contributor to that human variability is fatigue. Good human-machine system design exploits human strengths and protects the system from human weaknesses. This is a fundamental concept in human factors engineering (HFE). The human brings to a system much more powerful pattern recognition capabilities and decision-making skills than can be provided in software. However, the human also brings much more performance variability to a system than one finds in software and modern hardware.

4.3.2. Sources of Variability

Incomplete training and lack of currency are sources of human variability. When novices are learning to operate a complex system, they display a learning curve. Initially, their performance is quite poor and variable, but they learn the basics quickly. Next, their performance is noticeably better, on average, but still more variable than desired. Finally, as they approach the expert user level, their average performance is quite good and it varies only a small amount. Similarly, when expert users become "rusty" in the operation of a complex system, their performance may be more variable than desired until they return to their expert level.

Additionally, one of the primary hallmarks of human fatigue is performance variability. This is due to large amplitude, moment-to-moment fluctuations in attentiveness associated with fatigue. One's average performance may be acceptable, but there are brief periods when responses are extraordinarily delayed or absent ("mental lapses"). A good example of a mental lapse is missing your exit from the freeway. We often call this "distractibility" and note that fatigued system operators are more easily distracted than nonfatigued operators.

4.3.3. Sources of Fatigue

Sleepiness and fatigue are different human states. You may recall times when you were fatigued but not sleepy. However, when we have asked workers for numeric ratings of sleepiness and fatigue across many days and nights of demanding work, their two sets of ratings have correlated very strongly. Thus, it appears that in our day-to-day activities we perceive the two states as changing in parallel most of the time. For most purposes, you may view sleepiness and fatigue as being almost the same thing. We sort the generators of fatigue into the five categories: physical, circadian, acute, cumulative, and chronic.

4.3.4. Circadian Effects

There are normal, inherent, unavoidable, 24-hr rhythms in human cognitive and physical performance. Most of these circadian rhythms oscillate between a high point late in the day to a low point in the pre-dawn hours with a peak-to-trough amplitude of

about 5% to 10% of their average value. Human circadian rhythms are slightly longer than one cycle per day but are normally slaved, or entrained, to exactly one cycle per day by external time cues (often referred to by the German word for time cues, *Zeitgebers*), especially the daylight-darkness cycle.

Circadian-related fatigue falls into two major categories. The first is fatigue or sleepiness associated with attempting to work or function at times that coincide with the circadian trough. Personnel working on a night shift often experience this type of fatigue. The second is fatigue associated with a circadian rhythm that is disrupted because of some type of schedule change. Shift workers experience this type of fatigue for several days/nights after rotating to a new work/rest cycle (shift lag), and travelers experience this type of fatigue after traveling to a new time zone (jet lag). Note that the problem is not just that the rhythms are peaking and troughing at the wrong times with respect to external cues; they also fall out of synchronization with each other. These different types of loss of synchrony – with external cues and internally – both seem to contribute to feelings of *malaise*.

4.3.4.1 Jet Lag. The feelings of *malaise* and fatigue that accompany a time zone change that is faster than about one time zone per day. Jet lag occurs during the period of resynchronization of circadian rhythms to new external time cues, especially the daylight-darkness cycle.

4.3.4.2 Shift Lag. The feelings of *malaise* and fatigue that accompany a change from day work to night work and vice versa. Shift lag occurs during the period of attempted resynchronization of circadian rhythms to new external time cues. Compared to jet lag, the attempt to resynchronize to a night work and day sleep schedule occurs more slowly and is much less successful because the main time cue, the daylight-darkness cycle, tends to inhibit resynchronization.

4.3.5. Acute Fatigue

Acute fatigue builds up normally and unavoidably within in one waking period, but recovery from acute fatigue occurs as the result of one good-quality, nocturnal sleep period.

4.3.6. Cumulative Fatigue

Cumulative fatigue builds up across several waking and duty periods when there is inadequate recovery (due to inadequate sleep) between the duty periods. Recovery from cumulative fatigue cannot be accomplished in one good-quality, nocturnal sleep period.

4.3.7. Chronic Fatigue

Chronic fatigue may set in after 1 to 2 wk of cumulative fatigue. The symptoms of chronic fatigue include:

- The desire to sleep
- Apathy
- Substantial impairment in short-term memory or concentration
- Muscle pain
- Multi-joint pain without swelling or redness
- Headaches of a new type, pattern, or severity
- Unrefreshing sleep
- Post-exertional malaise lasting more than 24 hr

These symptoms are similar to those of chronic fatigue syndrome (CFS**)**; however, unlike CFS, the cause is known (continuing cumulative fatigue) and it occurs much sooner than the 6-mo diagnostic requirement for CFS. The Air Force Safety Center has in the past called chronic fatigue "motivational exhaustion." While this label accounts for only one of several possible symptoms of chronic fatigue (apathy), it describes well the attitude that one observes in a person with chronic fatigue. It is possible that the long-term presence of chronic fatigue in an individual is one of the causes for the illnesses associated with chronic night work or shift work (para 4.3.9).

4.3.8. Physical Fatigue

There are a number of physiological costs associated with physical effort. Physical fatigue, physiological costs are metabolic in nature and may include, among others:

- Elevated whole-body metabolism associated with nonsedentary work, like jogging
- High levels of specific muscle anaerobic metabolism associated with lifting or with the maintenance of a single posture for a long time
- Relatively high heart muscle (myocardial) metabolic demands due to the combination of poor physical conditioning and high physical workloads
- Increased potential for the triggering of central nervous system sleep systems (falling asleep on the job) associated with sleep disruption

Fatigue may also lead to injury. An acute physical stress that exceeds connective-tissue limits may lead to a sprain or strain of a joint. Lesser physical stresses, repeated for days, months, or years, may cause cumulative or repetitive stress injuries. Sedentary work in the absence of exercise and nutritional limitations may lead to morbid obesity and to cumulative trauma of the back. Excessive aerobic effort, especially in a hot environment like a hot aircraft on the ramp, may lead to heat exhaustion and to myocardial ischemia, raising the possibility of heart muscle damage.

On the other hand, exercise increases heart and lung fitness while reducing stress, anxiety, and insomnia. It also raises endorphin levels -- the natural "mood elevators" produced by the brain in response to physical exercise. Endorphins reduce

pain, relax muscles, suppress appetite, and produce feelings of well being. As a result, sleep will be deeper and more restful. Even something as simple as brisk walking can have a positive effect, if done regularly. The best time to exercise for maximum sleep efficiency is at noon, or between 5 p.m. and 7 p.m. Excessive exercise (beyond one's capacity) that occurs within several hours before trying to sleep can disrupt sleep.

Physical fatigue does not seem to interact much with cognitive fatigue. However, circadian rhythms do affect physical strength and endurance. These usually vary about 10%, with a peak in the late afternoon/early evening and a trough in the hours around dawn.

4.3.9. Nature of Fatigue

Fatigue is ubiquitous, pervasive, and insidious. By ubiquitous we mean that fatigue affects everybody. There are individual differences: a few people are truly more resistant to fatigue effects than others. Many other people feel, without basis, that they are more resistant to fatigue effects than others. This misperception may cause them to form ill-advised intentions and/or to make bad decisions.

By pervasive, we mean that fatigue affects everything we do, physically and cognitively. Again, there are individual differences. In the physical domain, there are those who are inherently able to train to much greater levels of strength and endurance than the rest of us. This may also be true in the domains of cognition and attention: some people seem inherently less susceptible cognitively than most others.

By insidious, we mean that often when we are fatigued, we are quite unaware of how badly we are performing. Most people have experienced the attention lapse associated with mild fatigue when they miss a freeway exit or realize suddenly that they don't remember the last mile or two driven on the highway. Similarly, most people recovering from a period of physical, emotional, or cognitive stress have uttered the phrase, "I didn't realize how tired I was!"

Understanding these aspects of fatigue, it is easy to see how we may become tricked into conducting safety-sensitive jobs such as flying, driving, operating weapons, and making command and control decisions when we are too fatigued to be safe. If we think that we are more resistant to fatigue than we really are, and if we don't realize that we are very fatigued, then we slog on toward the goal while making poorer decisions, accepting more risk, and being more easily distracted than we should. This is not an intelligent approach to operations, though it has been the accepted approach on many occasions.

According to the National Sleep Foundation, lack of sleep is associated in the short term with irritability, impatience, anxiety, and depression. These problems can upset job and family relationships, spoil social activities, and cause unnecessary suffering. In the long term, shift workers may experience more stomach problems (especially heartburn and indigestion), menstrual irregularities, colds, flu, weight gain, and cardiovascular problems than day workers.

4.3.10. Quantitative Estimation of Fatigue

Fortunately, the biological changes and rhythms that cause fatigue-induced declines, lapses, and variability in human performance are relatively lawful and predictable. There are quantitative models and simulations, implemented in software, that allow us to estimate and predict the timing and severity of fatigue episodes, given some information about when and how much people sleep. A world-class applied model (or simulation) was developed primarily with Department of Defense funding. The Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) applied model integrates quantitative information about (1) circadian rhythms in metabolic rate, (2) cognitive performance recovery rates associated with sleep and cognitive performance decay rates associated with wakefulness, and (3) cognitive performance effects associated with sleep inertia to produce a three-process applied model of human cognitive effectiveness.

The Fatigue Avoidance Scheduling Tool (*FAST*™) is based upon the SAFTE applied model. *FAST*™ was developed initially as an Air Force product under the Small Business Innovation Research program to deal specifically with Air Force scheduling issues. At this writing, it is a Windows® program that estimates the average effects of various work-rest schedules on human cognitive performance based on information supplied about an individual's work and sleep patterns. These data may be entered into the computer in any of several formats.

Alternatively, there are two other world-class, quantitative models that may be used to help predict fatigue occurrence in shift work. One is the System for Aircrew Fatigue Evaluation (SAFE), which focuses mainly on aviation issues (Civil Aviation Authority, 2005). The other is the Fatigue Audit InterDyne™ (FAID), which focuses on estimating the risk of fatigue-induced errors (http://faid.interdynamics.com/). FAID is authorized for use as a tool in the implementation of fatigue risk management systems in Australian civil transportation sectors (aviation, rail, highway, maritime) and military operations. It has also been used in specific implementations in the U.S., Canada, the UK, South Africa, and Southeast Asia.

At a more simplistic level, the level of fatigue in personnel can be assessed by using the USAFSAM Fatigue Scale, developed in the early 1980s and used in many laboratory and field research studies:

1. Fully alert; wide awake; extremely energetic
2. Very lively; responsive; but not at peak
3. Okay; somewhat fresh
4. A little tired; less than fresh
5. Moderately tired; let down
6. Extremely tired; very difficult to concentrate
7. Completely exhausted; unable to function effectively

A score of 6 or 7 should disqualify an individual from performing safety-sensitive work such as driving vehicles, operating aircraft, using a weapon, making command-and-control decisions, etc. The fatigue scale may be used repeatedly to look for trends. Additionally, a one-time assessment of sleepiness may be accomplished with the Epworth Sleepiness Scale:

How likely are you to doze off or fall asleep in the following situations, in contrast to just feeling tired? Though you may have not done many of these things recently, please estimate their effect on you the best you can.

Use this scale, and enter one number on each line:

0. Would *never* doze
1. *Slight* chance of dozing
2. *Moderate* chance of dozing
3. *High* chance of dozing

a______ Sitting and reading
b______ Watching TV
c______ Sitting inactive in a public place; for example, a theater or meeting
d______ As a passenger in a car for an hour without a break
e______ Lying down to rest in the afternoon when circumstances permit
f______ Sitting and talking to someone
g______ Sitting quietly after lunch without alcohol
h______ In a car while stopped for a few minutes in traffic

A sum of 10 or greater is cause for concern if safety-sensitive tasks are to be performed.

4.3.11. Biology, Night Work, and Shift Work

In terms of human biology, night work is a crime against nature. We cannot see well in the dark. Our metabolism slows overnight until it reaches a low point, usually during the pre-dawn hours. In the dark, the pineal gland at the base of the brain releases the hormone melatonin, which, in turn, makes us feel drowsy. At night, the likelihood compared to daytime that we will sleep when lying down comfortably with our eyes closed is very high. Our brains and bodies are designed to sleep at night and to work during the day. Thus, when an operation requires staffing 24 hr per day, 7 days per week (24/7), there is no "good" shift work schedule to be found because some personnel simply will be forced to work at night. However, there are an infinite number of possible shift work schedules. The principle-based approach to scheduling described in the AF Research Laboratory's shift work scheduling manual (Miller, 2006) constrains the infinite number to those schedules that are simple, practical to implement, and least harmful to worker health, job performance, and attitude. Thus, the constraints should help produce the least-injurious schedule for a given operation.

4.3.12. Safety and Productivity in 24/7 Operations

According to the National Sleep Foundation, people who are sleep deprived think and move more slowly, make more mistakes, and have difficulty remembering things. These negative effects lead to lower job productivity and can cause accidents. One of the leading shift work research centers combined the findings from numerous field studies conducted in companies engaged in 24/7 shift work (Folkard & Tucker, 2005). The results of their efforts show you what to expect in terms of safety and productivity when shift work is used. The combined data from field studies showed that:

“Risk [of injuries and accidents] was found to increase in an approximately linear fashion across the three shifts, … 18.3% on the afternoon shift … 30.4% on the night shift, relative to that on the morning shift.” (Fig. 4.3.12-1, from eight studies)

“ … ‘real-job’ speed and accuracy measures are only above average between 0700 h and 1900 h; at all other times efficiency is likely to be relatively impaired, especially so during the early hours of the morning.” (Fig. 4.3.12-2, from three studies)

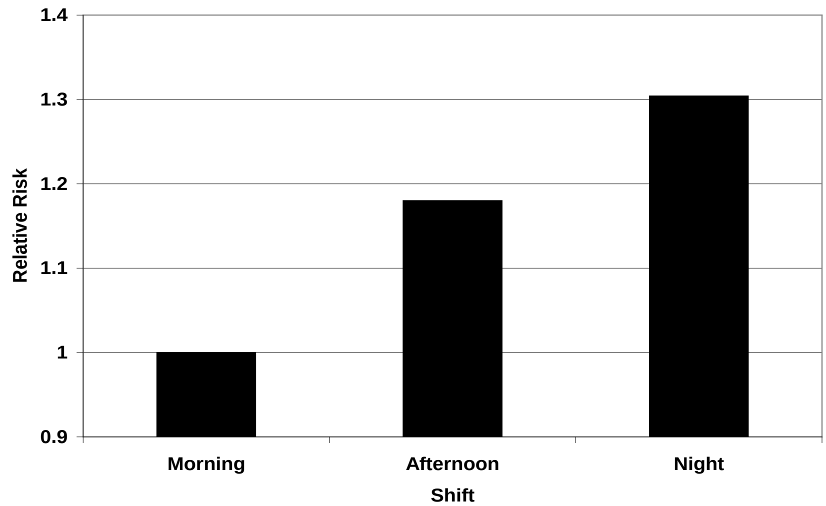

Figure 4.3.12-1. Relative Risk of Injuries and Accidents Across the Three Shifts (data from 8 field studies; redrawn from Folkard & Tucker, 2003)

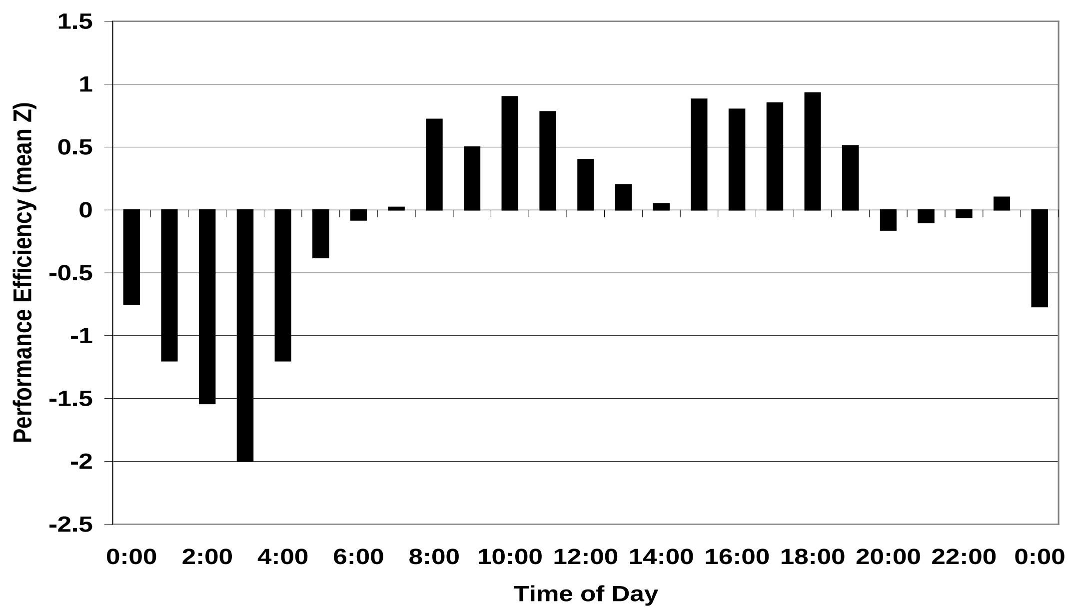

Figure 4.3.12-2. Relative Real-Job Speed and Accuracy Measures Across the Hours of the Day (data from 3 field studies; redrawn from Folkard & Tucker, 2003)

There is an important caveat with respect to this and subsequent graphs concerning the relative risk of injury and accidents in industry: it is highly likely that injuries and accidents are underreported in industry. In theory, the use of a relative risk measure accounts for that underreporting. However, if the underreporting pattern varies across shifts and/or across days of the week, then the correction may not be valid.

Field-study data also indicated that, in the short term, acute fatigue may be offset to some degree by work breaks (Fig. 4.3.12-3). Following a 15-min break after 2 hr of continuous work, "risk [of injuries and accidents] rose … approximately linearly, between successive breaks … risk had doubled by the last 30 min period." There was "… no evidence that this trend differed for the day and night shifts." (Of course, there is a higher absolute risk during the night shift, as shown in Figure 4.3.12-1). This risk pattern argues for a high frequency of rest breaks. However, if the handing-over of a task from worker to worker involves high risk, then the risk-related benefit of frequent breaks may be lost.

Also according to the National Sleep Foundation, the risk of workplace accidents and automobile crashes rises for tired shift workers, especially on the drive to and from work. People think that opening the car windows or listening to the radio will keep them awake. However, studies show that these methods do not work. In fact, attempts to use these countermeasures should be taken as a signal of fatigue and the need to pull over immediately. Sleepiness at the end of a shift should signal the need for a nap before driving home. Allow 5 to 20 min for sleep inertia (feelings of grogginess and/or sleepiness that occur immediately after waking up) to wear off, as needed.

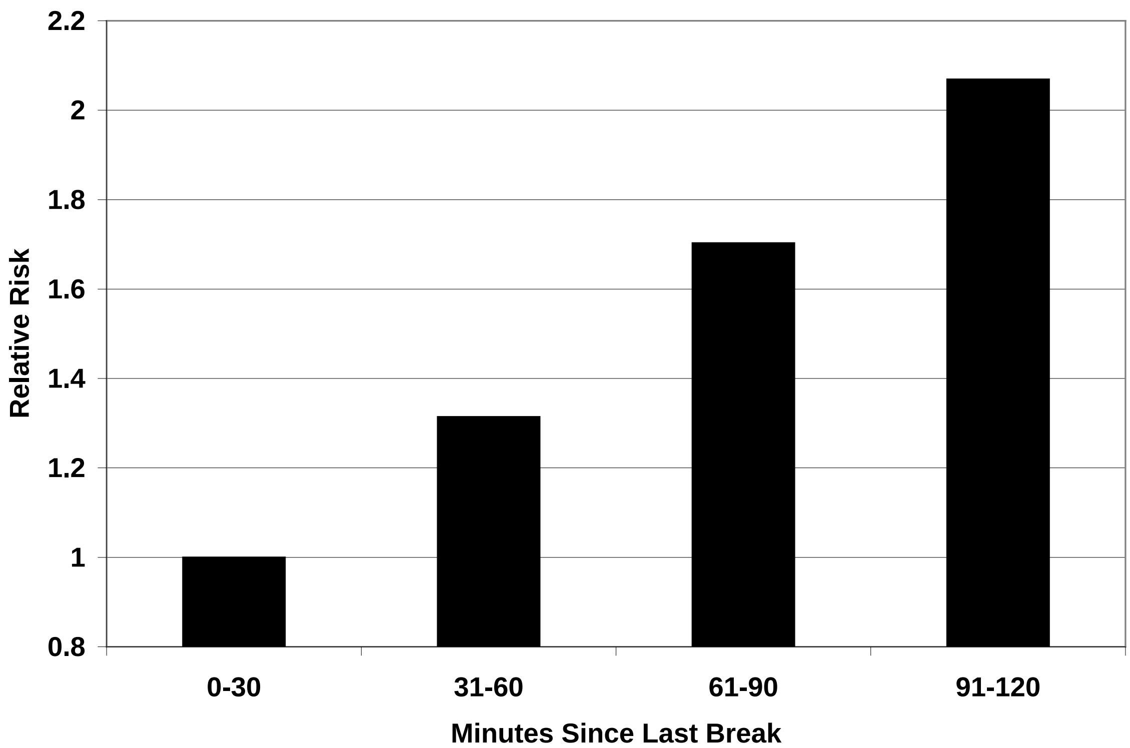

Figure 4.3.12-3. Relative Risk of Injuries and Accidents During the Four 30-Min Work Periods Following a 15-Min Break (data from 1 field study; redrawn from Folkard & Tucker, 2003)

Follow these steps to arrive home safely:

- Carpool, if possible; have the most alert person do the driving.
- If sleepy, stop to nap, but do so in a locked car in a well-lit area. Allow 5 to 20 min for sleep inertia to wear off, as needed.
- Take public transportation, if possible.
- Drive defensively.
- Don't stop off for a "night cap." Alcohol, combined with fatigue, increases the risk of a fatigue-related accident quite sharply.

These actions may often be viewed as impractical or unnecessary because night workers almost always drive home safely after their night shift. Similarly, drunk drivers almost always drive without accidents. However, just as the Air Force does not condone drunk driving, we should not condone the idea of sending a highly fatigued driver out the gate of an Air Force base and into traffic or a long commute on a boring highway. A recent court case provided an example of what can happen to a fatigued night worker on his way home (Escoto, 2001). Nabors Drilling Co. employee Roberto Ambriz fell asleep at the wheel on Texas State Highway 490 near the city of Raymondville about 20 min after ending his graveyard shift in March of 1998. His pickup truck went into the oncoming lane, striking a Dodge pickup being driven by Martin Rodriguez. Rodriguez and his three passengers died at the scene, and Ambriz died from his injuries 2 days later. A decision was won against the employer for failure to train employees who work graveyard shifts about the risks of driving after working a graveyard shift.

4.3.13. Practical Recommendations

Air Force personnel and supervisors should act to improve the practicality of the preventive actions above whenever possible. For example, the use of public transportation may delay the onset of daytime sleep for night workers substantially. Thus, supervisors should consider providing and requiring the use of a carpool with a rested, trained driver for night workers with relatively long commutes. Similarly, supervisors should consider providing and requiring the use of pre-drive napping quarters for night workers and fatigued workers who are ending their shifts. Supervisors should also consider added training sessions for night and rotating-shift workers concerning defensive and intoxicated driving.

The following recommendations may be applied as fatigue countermeasures in the 24/7 workplace (also, see Miller, 2006):

- Schedule a good-quality break of at least 15 min once every 2 hr or more frequently.
- Whenever safe and acceptable, insert a nap into the duty day. Don’t worry about nap length – any sleep is good. Allow at least 30 min after the nap before performing safety-sensitive jobs.
- Keep duty periods relatively short – no more than 8 hr long.
- Schedule no more than three night shifts in a row.
- Schedule at least 24 hr of uninterrupted rest after night shifts.
- Schedule days off in continuous periods of at least 3 days.

The following recommendations may be applied at the individual level as general fatigue countermeasures:

- Reduce stress as much as possible.
- Exercise to stay fit.
- Keep mentally stimulated.
- Eat properly.
- Stop smoking.

The following recommendations may be applied at the individual level as sleep aids:

- Establish a bedtime ritual.
- Take a warm bath before bed.
- Noise -- If you can't avoid noise, try soft earplugs or create soft white noise by running a fan or air conditioner or setting the tuner of a radio between two stations.
- Light level -- Use dark fabric to block windows or the rim of a door. Or, try eyeshades.
- Temperature and humidity – Try to maintain a comfortably cool environment (about 70 °F) and 60%-70% humidity. A humidifier or dehumidifier may also provide soft white noise.
- Security -- As part of your bedtime ritual, check door locks and close windows.
- Clocks -- Hide illuminated clocks from view. If you've established a regular sleep schedule, you may not even need an alarm to wake you up.
- Cleanliness -- Keep the bedroom clean and free of clutter. Piles of clothes, reports, and bills induce feelings of stress.
- Nightclothes -- Choose loose-fitting, soft garments that breathe, in the right weight for your bedroom's temperature.
- Bed sheets and pillows – Use bed sheets that are clean, cool, and comfortably soft. Use a good pillow that puts you in a healthy sleep posture.

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Concepts

- Fatigue avoidance scheduling tool (FASTTM)
- Sleep, activity, fatigue, and task effectiveness (SAFTE)
- Human factors engineering (HFE)

Vocabulary

- Acute fatigue
- Chronic fatigue
- Chronic fatigue syndrome (CFS)
- Circadian
- Cumulative fatigue
- Jet lag
- Physical fatigue
- Shift lag

4.4. Human Systems Integration

Robert M. Lindberg
William Kosnik, Ph.D.

4.4.1. Human Systems Integration Perspective

Every Air Force system involves airmen from weapons to medical to human resource management systems; there are no unmanned systems within the Air Force. In today's complex warfighting environment, and even more so in the future, airmen require the same, if not greater, attention and care as any acquired, modernized, or procured system (traditionally thought of as the hardware, software, and data products). The complexity associated with achieving human performance, as a component of total system performance, compared to even the most sophisticated military technology and concept of operations (CONOPS) mandates a robust human systems integration (HSI) program integrating nine crosscutting domains (Table 4.4.1-1). From this perspective, HSI must span the entire spectrum of force activities, from concept refinement, research and development, personnel selection, through acquisition and fielding, to operational employment and disposal.

4.4.2. Warfighting Capability

Militarily useful weapons systems achieve superior warfighting capability through total system performance (Fig. 4.4.2-1). In an operational context, warfighting capability is best represented by probability to kill (Pk), operational availability (Ao), and operator reliability (Rop), better known as human performance. Central to Pk, Ao, and Ro is who, what, when, where, and how the weapons systems will be used (CONOPS); through which technologies (hardware, software, and data products); and by what group of airmen performing the mission.

To deliver militarily useful, operationally suitable, and effective weapons systems while delivering total systems performance and minimizing total ownership cost, the Air Force is building out a solid human performance and HSI program as directed by Health Services (AFDD 2-4.2, 2002), Operation of the Defense Acquisition System (DoDI 5000.2, 2003), and Operations of Capabilities Based Acquisition System (AFI 63-101, 2005). HSI explicitly integrates the nine crosscutting domains (Fig. 4.4.2-2). This integration, in simple terms, leads to these outcomes (i.e., human-machine interface design; knowledge, skills, and abilities of airmen; work distribution between airmen and the technology; and whether airmen are qualified, rested, motivated, vigilant, and healthy) during all phases of military operations. Leading to and underpinning human performance are human capabilities and competencies, work to be performed, and human fitness for duty.

Table 4.4.1-1. Human Systems Integration Domains

 **Human Factors Engineering—**the comprehensive integration of human capabilities and limitations (cognitive, physical, sensory, and team dynamic) into systems design to optimize human interfaces to facilitate human performance in training operation, maintenance, support, and sustainment of a system. **Environment—**in the context of HSI, environment includes the conditions in and around the system and the concepts of operation that affect the human's ability to function as a part of the system as well as the requirements necessary to protect the system from the environment (e.g., radiation, temperature, acceleration forces, all-weather ops, day-night ops, laser exposure, air quality within and around the system, etc.). **Safety—**the application of systems engineering and systems management in conducting hazard, safety, and risk analysis in system design and development to ensure that all systems, subsystems, and their interfaces operate effectively, without sustaining failures or jeopardizing the safety and health of operators, maintainers, and the system mission.	**These nine domains are defined:** **Manpower—**the number and mix of personnel (military, civilian, and contractor) authorized and available to train, operate, maintain, and support each system. **Personnel—**the human aptitudes, skills, and knowledge; experience levels; and abilities required to operate, maintain, and support a system at the time it is fielded. **Training—**the instruction and resources required providing personnel with requisite knowledge, skills, and abilities to properly operate, maintain, and support a system. **Occupational Health—**the consideration of design features that minimize risk of injury, acute and/or chronic illness, or disability and/or reduce job performance of personnel who operate, maintain, or support the system. **Habitability—**factors of living and working conditions that are necessary to sustain the morale, safety, health, and comfort of the user population that contribute directly to personnel effectiveness and mission accomplishment and often preclude recruitment and retention problems. **Survivability—**the ability of a system, including its operators, maintainers, and sustainers, to withstand the risk of damage, injury, loss of mission capability, or destruction.

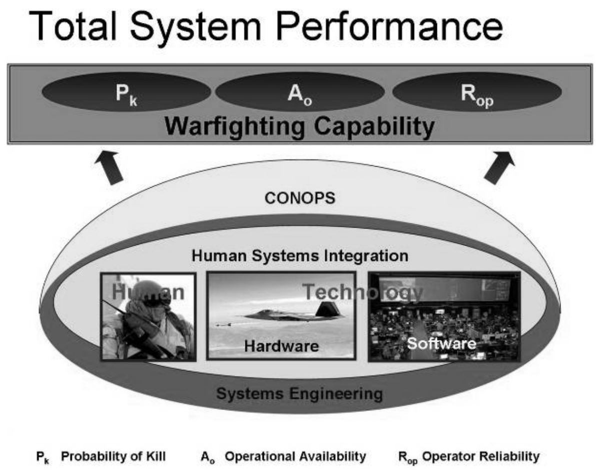

Figure 4.4.2-1. Total System Performance (adapted from Bost, 2005)

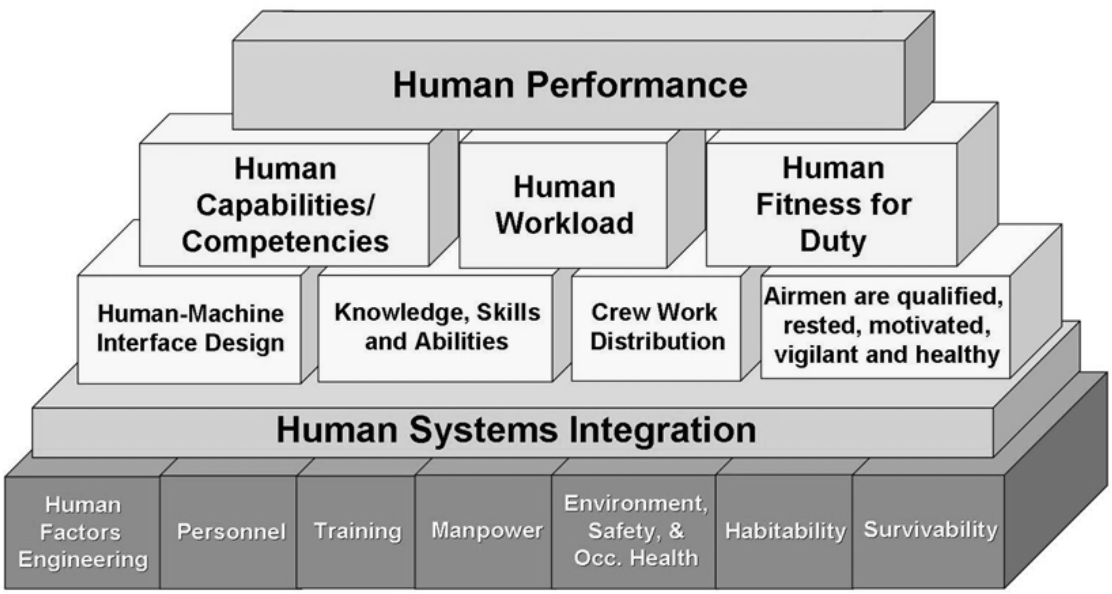

Figure 4.4.2-2. Building Blocks of Human Systems Integration (adapted from Bost, 2005)

4.4.3. What is Human Systems Integration?

Many people view HSI as being primarily concerned with the interface between the human and machine and therefore synonymous with human factors engineering. This view actually encompasses only a single domain within HSI. In the broadest sense, HSI is an effort to make human performance, within the context of total systems performance, a top priority in materiel and nonmateriel solutions. HSI is a process to ensure systems are affordably conceived, designed, and developed to optimize combat capability. This total systems approach focuses on human performance and ensures

capabilities, limitations, opportunities, and risks are identified and managed throughout the process within the Defense Acquisition, Technology, and Logistics Life Cycle Management Framework (Fig. 4.4.3-1). HSI starts when the Joint Capabilities Integration and Development System (JCIDS) process begins as indicated in Figure 4.4.3-1. If a nonmateriel solution (e.g., change in tactics, techniques, and procedures) is selected, HSI considerations would appear in the Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities (DOTMLPF) change requirement document (DCR) rather than in an initial concept document (ICD).

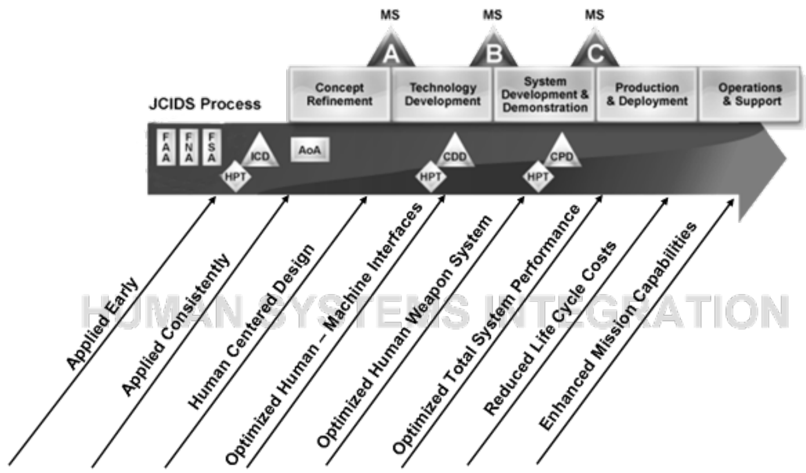

Figure 4.4.3-1. Defense Acquisition, Technology, and Logistics Life Cycle Management Framework (Sys 260 Course, 2008)

An effective HSI program requires planning, integration, and timely application. First, acquisition planning groups such as high performance teams (HPTs) and integrated product teams (IPTs) must incorporate the nine functional HSI domains into program requirements. Traditionally, the HSI domains (Table 4.4.1-1) have been employed as separate entities, typically using a "stovepipe" approach where each discipline is applied individually in the acquisition process. Proper implementation of HSI by HPTs and IPTs involves trade-off analyses to achieve an optimal design. This provides a common basis upon which to make knowledgeable decisions.

Second, HSI integrates the three components of a weapons system – hardware, software, and personnel (DoD 5001.1, 2005, E1.29) – to optimize total system performance. Past experience has shown that acquisition programs have frequently failed to consider the human component as part of the system, resulting in poor task allocation between hardware, software, and human performance.

Third, HSI is applied ideally during the JCIDS process, well before the concept refinement phase is begun, where it is mostly likely to positively affect total system performance and life cycle costs. Early application of HSI provides the best opportunity to maximize return on investment (ROI) and system performance. In reality, though, HSI must often be applied to legacy systems that are well along the life cycle chain. As shown in Figure 4.4.3-1, however, HSI may be applied anywhere in the system life cycle. Aerospace physiologists (APs) are most likely to encounter fielded weapons systems in the sustainment and operations phase of the life cycle. It is here that that the AP may apply HSI to identify performance gaps, failures, and incompatibilities that may limit optimal functioning or cause hazardous conditions.

4.4.4. How Is HSI Applied?

For new weapons systems, the AP may be required to perform an HSI assessment at the beginning of the acquisition cycle to ensure compliance with human-centered design goals. In this instance, a bottom-up approach is taken, starting with an analysis of human performance requirements at each of the HSI domains. A comprehensive plan should be developed to address each HSI domain requirement. The HSI plan should support each phase of the life cycle (concept refinement, technology development, system development and demonstration, production and deployment, and operations and support). Requirements are derived from the operational user's identification of gaps in current capability through a mission task analysis. These gaps can be filled through changes in doctrine, manpower, training, and materiel solutions. Trade-off analyses are conducted to ensure that the final solution addresses the user's needs by the most effective, safe, and affordable means possible. Requirements developed in the HSI plan are transmitted to system developers through a series of progressively more detailed documents such as the initial capabilities document (ICD), capabilities development document (CDD), capability production document (CPD), and request for proposals (RFP) that support the acquisition process. HSI requirements are addressed in capability documents with associated key performance parameters (KPP) and key system attributes (KSA). This allows HSI requirements to become measurable, which is necessary for effective implementation in the acquisition stream.

4.4.5. HSI – Why Now?

The Air Force currently faces challenges that will affect the way it prepares for, conducts, and wins conflicts in the 21st century. Financial constraints are forcing the Air Force to become far more efficient than ever before with both materiel and human resources. The Air Force can no longer rely on the cost savings of a smaller force for the recapitalization of legacy systems. This current climate is forcing the Air Force to look more closely at balancing the contributions and costs of airmen, policy, and technology (Retelle and Chatelier, 2005). Considering the significant mission and personnel challenges the Air Force will face in the future, along with the unyielding threat environments, it is imperative that the human element of Air Force systems be continually addressed and optimized.

HSI enables the Air Force to leverage its human and technological resources to meet the challenges of the 21st century. By building the human into systems at every level—through capability definition, acquisition, systems development, training and education, operations, and maintenance—HSI can make the most of existing resources throughout the life cycle of its weapons systems. It is essential that HSI be considered early in, as well as throughout, the Defense Acquisition, Technology, and Logistics Life Cycle (Retelle and Chatelier, 2005).

4.4.6. The Aerospace Physiologist's Role in Human Systems Integration

The mission of Aerospace Physiology is to enhance warfighter performance through aerospace medical training, education, research, and consultation. By its very nature, Aerospace Physiology is "human centered." Aerospace Physiology has faced HSI domain issues throughout the history of aviation in a continual effort to maximize warfighter performance. Nevertheless, in the past there has been a tendency to apply HSI on a piecemeal basis with little consideration of the entire process. Costly modifications, unsafe systems and operations, excessive life cycle costs, and technology poorly suited to the warfighter have plagued AF weapons systems due to a lack of or improper HSI application. Furthermore, as missions become more complex and the flight environment more demanding, the systematic application of HSI is more critical than ever to ensure optimal performance and seamless integration of systems across the entire enterprise.

Organizations must focus attention within the JCIDS (CJCSI 3170.01, 2007) and the operation of the Defense Acquisition System (DoDI 5000.2, 2003) processes as illustrated in Figure 4.4.3-1. To do so, HSI requires highly qualified practitioners, such as aerospace physiologists, who can effectively and affordably integrate and evaluate human capabilities in new and existing weapons systems. More specifically, aerospace physiologists center attention on total system performance by integrating trade-offs and identifying capability gaps within and across the HSI domains of manpower, personnel, training, human factors engineering, environment, safety, occupational health, survivability, and habitability.

Aerospace Physiology is one of many career fields that make up the HSI community of practice (Fig. 4.4.6-1). These fields contribute specialized knowledge of the human – physiology, cognition, psychology, behavior – along with knowledge of engineered systems – engineering, computer science, and mathematics – to optimize total system performance. The AP facilitates the integration of human and machine by applying HSI principles to the engineering systems that serve to sustain and augment human physiological processes. As such, HSI principles and practices may be applied to virtually every aspect of Aerospace Physiology as described in this handbook.

4.4.7. HSI as a Process Model of Human Performance

Aerospace Physiology grew out of efforts to cope with the demands of a harsh flying environment. When analyzed from a human performance perspective, the missions of aerospace physiology conform to an HSI process model. This handbook provides many examples of Aerospace Physiology missions that reflect the application of the nine HSI domains. For example, successful human flight required finding solutions to mitigate hazards of altitude, cold, acceleration, and other factors. In HSI these hazards are associated with environmental domain issues. Several sections in this handbook document efforts to solve these environmental problems that result in illnesses (performance gaps) such as hypoxia (section 3.2), decompression sickness (section 3.5), hypothermia (section1.7), and motion sickness (section 7.4).

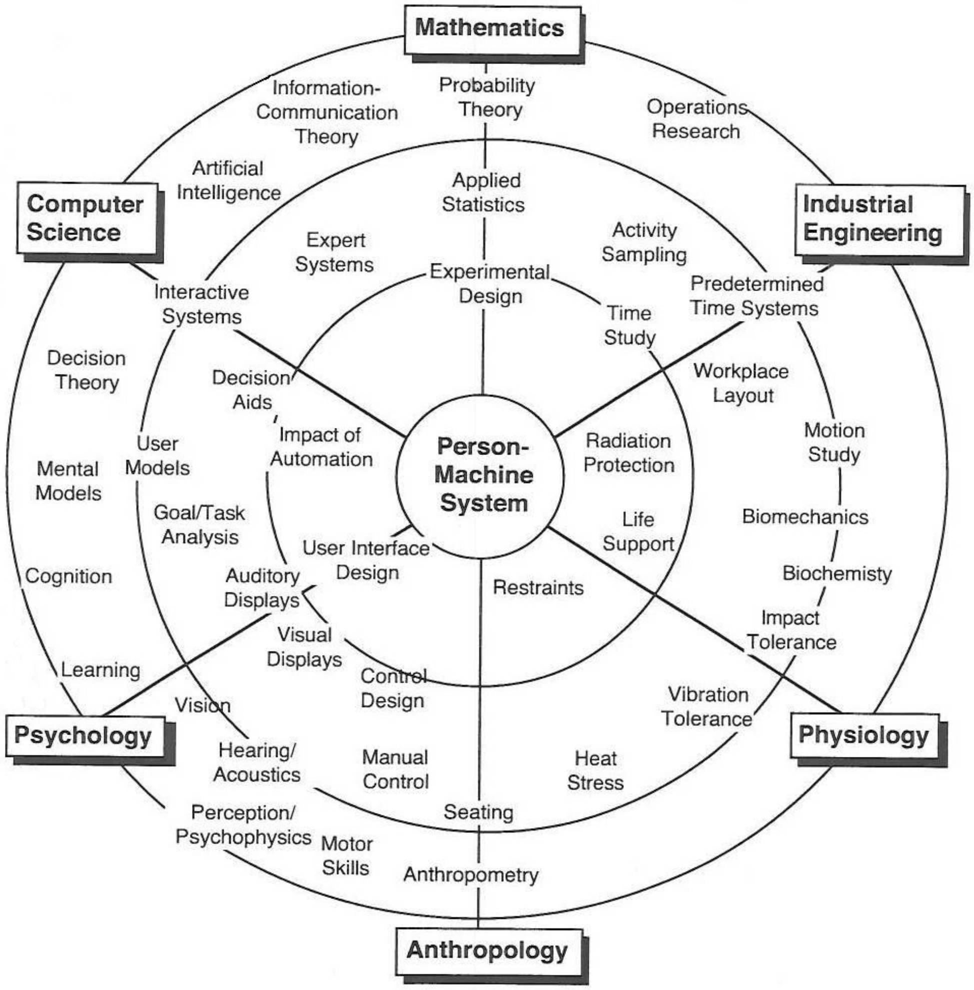

Figure 4.4.6-1. Career Fields Contributing to the Human-Centered Approach (adapted from Fogel, 1963)

Similarly, the combat environment has placed additional demands on the integrity and performance of the airman. Aerospace Physiology has responded to these threats by developing performance enhancement systems such as cockpit displays, NVGs, head-up displays (HUDs), anti-gravity suits (section 6), and protective devices such as ejection equipment and laser eye protection (sections 7.5 – 7.7). These solutions have emerged from requirements stemming from the human factors engineering, survivability, and safety domains.

An increasingly hostile combat environment has forced other aircrew adaptations as well. Advancements in speed, altitude, maneuverability, and endurance in high-performance aircraft have increased the amount of spatial disorientation, , vibration (section 7), noise (section 1.5), fatigue, and stress (section 4) that must be tolerated by the aircrew. Aerospace Physiology has developed countermeasures to cope with these problems by tapping into the domains of training, occupational health, and habitability. Solutions have come in the form of situation awareness training (section 4.5), noise and vibration reduction devices (sections 1.5 and 7.2), fatigue countermeasures, nutritional supplements, performance enhancers, and crew resource management training (section 4). The challenging flight environment and the need for protection and sustainment systems have driven the need to constantly select, train, and allocate

qualified personnel to the mission. These activities highlight the domains of manpower, personnel, and training (sections 4 and 7). These examples demonstrate that HSI continues to be the way of doing the business of Aerospace Physiology and that future application of HSI is necessary to provide trained, healthy, motivated, and capable airmen to the AF mission.

4.4.8. Capability Gap Analysis

One area where aerospace physiologists can provide leadership is capability gap analysis as mandated in Aerospace Medical Operations (AFI 48-101, 2005). Most often, the duties of the AP are required at the operations and sustainment phase of the system life cycle, that is, with fielded systems. However, no matter where the system resides in its life cycle, deficiencies and cost inefficiencies can be identified through a capability gap (Cap Gap) analysis. A Cap Gap analysis improves the aerospace team's understanding of the mission and human performance shortfalls in mission execution. This analysis is performed within each of the nine HSI domains by applying a rigorous set of performance metrics to identify performance gaps. Although it would not be expected that APs become experts in Cap Gap analysis, it would be advantageous for APs to have a working knowledge of the main issues to more fully understand how HSI may be applied to identifying problems at the mission level.

APs understand both the limits of human performance and methods for improving performance. They can, therefore, provide valuable inputs into the capabilities-based assessment process in terms of:

1. Addressing the limits of human performance (tasks, conditions, standards)
2. Conducting analyses on nonmaterial solutions and formulating DCRs
3. Ensuring HSI is addressed in high-level system measures of effectiveness (MOEs) in ICDs when a material solution is selected
4. Performing a Cap Gap analysis to determine the performance impact of a deficiency and its mitigation

As discussed in this handbook, physiological imbalances or deficiencies can lead to performance degrading outcomes. These deficiencies are viewed as performance gaps in HSI terms. A Cap Gap analysis consists of the following steps:

- Assess performance.
- Identify capability gap.
- Measure performance gap to quantify effect.
- Find root causes of gap with respect to the nine HSI domains.
- Perform trade-off analyses.
- Implement best solution to mitigate gap.
- Reassess performance.

The next two sections provide examples illustrating the use of a Cap Gap analysis in aerospace physiology operations.

4.4.9. Capability Gap Analysis in Unmanned Aircraft System Operations

The problem of fatigue in remotely piloted unmanned aircraft systems (UASs) serves as an apt example of a Cap Gap analysis (Miller et al., 2008; Tvaryanas & Thompson, 2006). This problem is addressed in detail in section 4.3. UAS crewmembers must often endure extended duty days, reduced crew size, and varying shift schedules (Walters et al., 2002) to accomplish long-endurance UAS missions. Stressful, long-duration missions often reduce operator effectiveness because of fatigue. A capability gap analysis can be used to assess the root causes of fatigue by applying the HSI process model. This approach offers a comprehensive method of identifying the sources of fatigue as well as a means for formulating remediation.

The problem of fatigue in shift workers can be attributed to both physiological factors (difficulty adjusting the circadian rhythm to a new work/rest schedule, strenuous physical activity) and institutional factors such as personnel selection, scheduling, training, and manpower (Miller et al., 2008). The human performance pyramid (Fig. 4.4.9-1) may be used to identify the relevant domains associated with fatigue using a top-down approach. A human performance gap (fatigue in this case) can be attributed to fitness for duty and workload issues. Fitness for duty, in turn, implies that the workforce is not adequately rested or vigilant. Workload issues might indicate an unbalanced workload distribution. These issues point to HSI domains of personnel, manpower, training, environment, occupational health, and safety. The relationship between fatigue and these domains is discussed in more detail below.

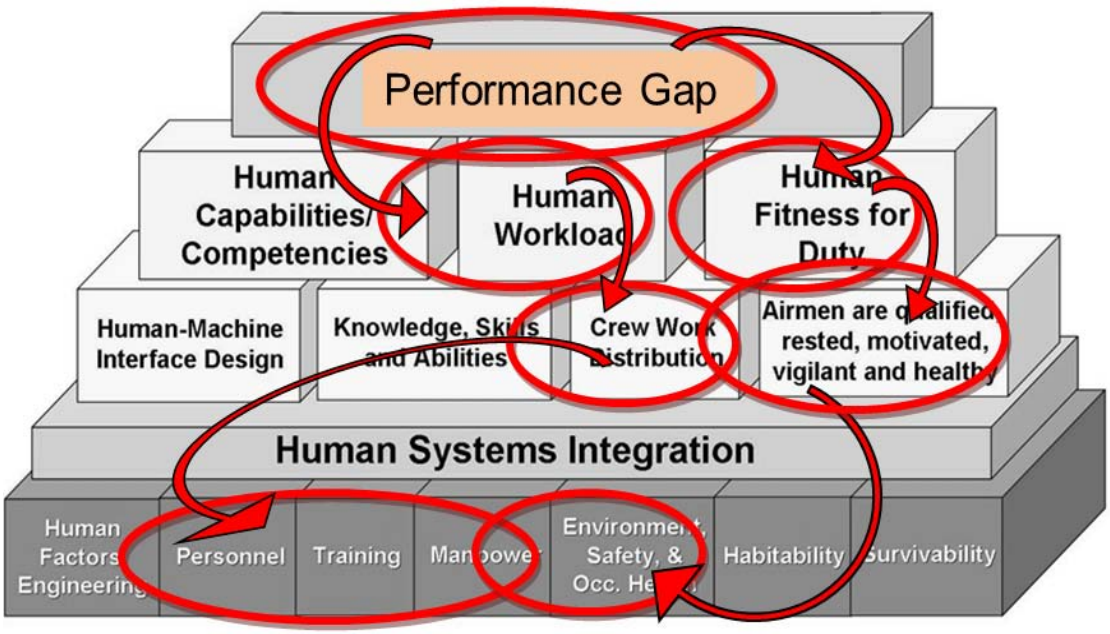

Figure 4.4.9-1. UAS Capability Gap Analysis Using the HSI Process Model (adapted from Bost, 2005)

4.4.10. Personnel and Training

UAS operators must have the necessary qualifications to operate the UAS. New personnel (i.e., sensor operators) are being trained for UAS operations that do not come from the traditional pilot/officer recruitment and training programs. Less emphasis is placed on manned pilot experience. Therefore, performance will be affected given the change in scope and initial experience level. Because few data exist on the performance aspects of UAS operators, the necessary knowledge, skills, and abilities may be underestimated, resulting in an excessive workload that may contribute to fatigue. Inadequate training may also add to workload demands and operator ineffectiveness.

4.4.11. Manpower, Safety, and Occupational Health

The aerospace physiologist may be most familiar with problems of fatigue stemming from issues of shift work. Although the advent of UASs may have generated the prospect of regular duty hours, this has not turned out to be the case. In fact, the long-endurance capability of UASs has necessitated round-the-clock staffing of ground control stations (GCSs). Inadequate staffing can result in longer shifts or shorter work/rest cycles. Shift work has a disruptive effect on circadian rhythms, as discussed in the section on Biology, Night Work, and Shift Work (Section 4.3.11), which can exact a heavy toll on health and safety through acute and chronic fatigue.

4.4.12. Trade-Off Analysis

A trade-off analysis can be used to vary the mix of solutions from several domains to find the most workable and cost-effective remediation. This may involve analyzing the benefits of adding resources from one domain to replace a solution from another domain that may be more costly. For example, one solution for mitigating fatigue may involve adding more experienced personnel or changing the ratio of work to rest days (manpower) rather than adjusting circadian rhythms (occupational health). Another solution might be to automate tasks to reduce the workload. Changes in habitability might also be considered. Family or other outside commitments could be adjusted to reduce stress and increase sleep periods. The aerospace physiologist should also be aware that trade-offs are not always a win-win situation. Often meeting performance requirements in one domain comes at a cost in another domain. Therefore, it is important to keep in mind that design decisions should be made around overall HSI requirements and not to specific domains.

4.4.13. Fatigue Mitigation Strategies

A successful Cap Gap analysis will point to potential remediation solutions. In a recent study on fatigue in UAS operations, Miller and colleagues suggested this mitigation strategy:

> The root problem for this population was not the shift system features themselves, but rather a lack of adequate manpower to provide sufficient recovery opportunities. Thus, at best, all that can be recommended are preventive and compensatory measures. While it is desirable to minimize

the number of consecutive night shifts, it is a reasonable alternative to continue the present schedule with multiple night shifts in succession and provide exposure to bright light during the night shift. While this will require modification of the GCS work environment (i.e., human factors engineering and habitability domains) and may not be immediately feasible, this feature should be considered in all future GCS design iterations. Other recommendations include educating supervisors and crewmembers as well as their spouses (i.e., training domain) on circadian rhythms, sleep disorders, the impact of shift work on family and social life, alertness strategies, safe driving, nutrition, physical activity, and coping with stress. Supporting medical personnel should ensure they have up-to-date knowledge of sleep disorders and shift maladaptation syndrome (i.e., training domain) and provide tailored medical surveillance of shift workers (i.e., occupational health domain). Finally, supervisors should implement methods to mitigate the danger of post-shift fatigue on driving safety by providing organizationally-sponsored car pools and offering work locations for post-shift naps prior to driving home (i.e., safety and habitability domains) (Miller et al., 2008).

By examining the mitigation of fatigue from the perspective of the different HSI domains, the AP will be led to the best possible solution(s). Applying the optimal solution is an HSI best practice that has the advantage of distributing the cost of the mitigation to achieve the least impact on the overall life cycle cost.

4.4.14. Capability Gap Analysis in Mishap Investigations

Human performance is optimized when human error is reduced to a minimum. As such, HSI may be used as a model for analyzing performance failures as well as for performance optimization. Nowhere is the analysis of human error more important than in mishap investigations. A thorough mishap investigation is essential to finding the causes of an accident and for preventing recurrences.

The root causes of mishaps can occur at any level of a mission operation, from the operator to higher levels in the chain of command. Traditionally, a mishap investigation focuses on the events immediately prior to the accident, but in reality the cause of an accident can be traced through many levels of the organization. An analytical model that recognizes the complexity of the causation chain has been instituted by the DoD. The DoD Human Factors Analysis and Classification System (HFACS) is the primary tool to identify the causes of mishaps across all levels of the causation chain. A description of HFACS and its value to performing mishap investigations is presented in section 8.4. HFACS classifies mishap causes as a series of hazardous conditions or behaviors that can occur at four different levels of the aviation enterprise (Reasons, 1990). These conditions, starting from the operator level, consist of:

1. Unsafe acts by the operator
2. Preconditions for unsafe acts
3. Unsafe supervision
4. Organizational breakdowns

A failure at any or all levels of the enterprise can result in a mishap. Consequently, preventative measures might need to be applied at several levels, not just at the operator level. A closer look at mishap analysis shows how the HSI process model can be used to help identify the sources of failure. Figure 4.4.14-1 gives the breakdown of the four classes of failure conditions. At the most basic level mishaps may be caused by errors associated with the operator. These acts include skill-based errors, judgment and decision errors, and perception errors. From the human performance process model (Fig. 4.4.2-2.), these errors flow down from the human capabilities and competencies block to the knowledge, skills, and abilities block and finally to the training and personnel domains. Unsafe acts ultimately can be traced to deficiencies in training or selection.

The second level of failure conditions, preconditions for unsafe acts, can involve environmental factors, individual states, or personnel factors. Environmental factors include stressors such as noise, thermal stress, or darkness. Adverse physiological states, such as fatigue, or psychological, cognitive, or perceptual factors can constitute predisposing conditions for failure. Such failures may be addressed as environmental, training, occupational health, human factors engineering, or personnel issues.

Errors at the supervisory level can also set up conditions for failure. Inadequate oversight, poorly planned violations, or supervisory violations are latent conditions that can lead to mishaps. The last tier of failure conditions can occur at the organizational level. Problems stemming from personnel, manpower, safety, survivability, or occupational health policies can filter down through the chain of command to set up preconditions for operator failure. By touching on all nine domains, the mishap investigator can be sure that all possible sources of failure conditions will be considered at every level of the organization.

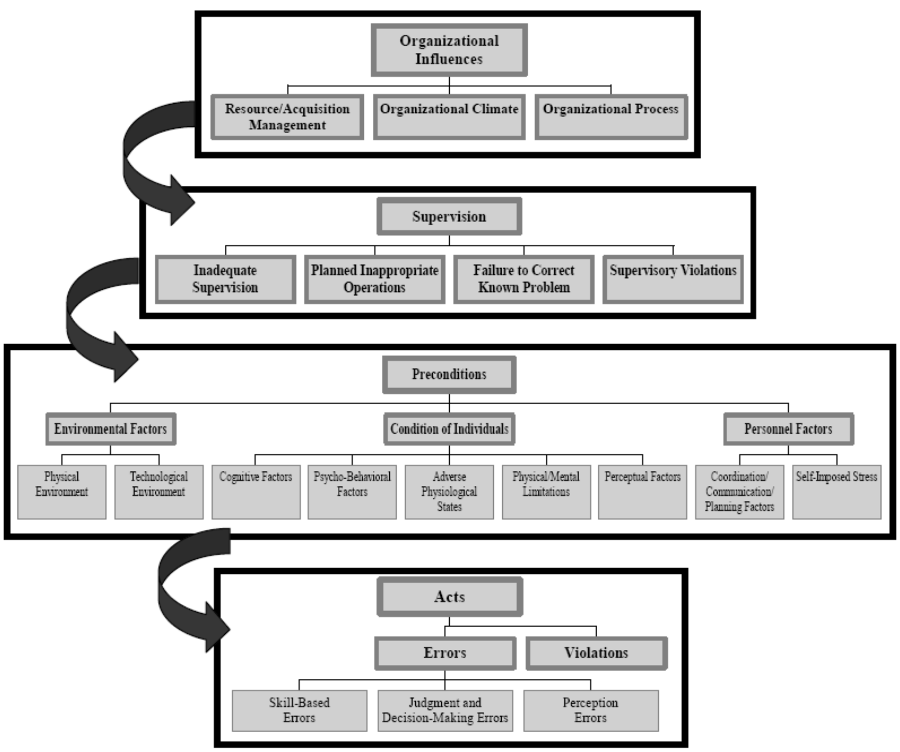

Figure 4.4.14-1. DoD Human Factors Analysis Classification Scheme for Mishaps Investigation (adapted from Wiegmann & Shappell, 2001)

4.4.15. Benefits of Human Systems Integration

The HASC Report (2006) notes that better program results can be achieved by an approach that focuses on long-term cost reduction. By applying a robust HSI program early in system development and acquisition, the program manager can maximize the overall return on investment in several important ways. Implementation of effective HSI practices and concentration on reducing the overall life cycle budget will tend to optimize system performance, reduce life cycle costs, provide more usable systems, and minimize occupational health hazards and opportunities for mishaps.

The Department of Defense cites that optimizing total system performance and minimizing the cost of ownership throughout a system's life cycle are the primary benefits of HSI. By adhering to HSI principles, the following benefits will also be realized:

- HSI becomes institutionalized as a "way of doing business" within the Defense Acquisition, Technology, and Logistics Life Cycle Management Framework.
- Requirements, information, issues, limitations, opportunities, and concerns from collaboration among the functional domains (Manpower, Personnel, Training, Human Factors Engineering, Environment, Safety, Occupational Health, Habitability and Survivability) will be applied from a system's pre-concept (inception) to disposal (grave) perspective.
- A human-centered approach to acquisition will be provided.
- The usability of systems through a focus on human-machine/technology interfaces will be improved.
- Warfighter and mission capabilities will be enhanced.
- System design will be optimized through an analysis of alternatives (AoAs), trade-off studies, and HSI tool use.

For Aerospace Physiology to fulfill its mission, it must continue to develop systems that support and enhance warfighter capabilities. The warfighter requires weapons systems that can be used effectively, safely, and without a large retraining component. The adoption of HSI principles and practices will ensure that Aerospace Physiology remains at the forefront of optimizing warfighter performance.

4.4.16. Training Opportunities

- AF Institute of Technology (AFIT) Courses @ http://www.afit.edu/ls/index.cfm
  - SYS 160, *Introduction to Human Systems Integration Course*
  - SYS 161, *HSI in Systems Capabilities Requirements Course*
  - SYS 162, *HSI Roadmap Course* (Under Development)
  - SYS 260, *HSI in Defense Acquisition Management* (Under Development)
- HSI Community of Practice (CoP)

https://afkm.wpafb.af.mil/ASPs/CoP/EntryCoP.asp?Filter=HP-HS

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Concepts

- Fatigue mitigation strategies
- Human systems integration (HSI)
- Human Factors Analysis and Classification System (HFACS)

Vocabulary

- High performance teams (HPTs)
- Human factors engineering (HFE)
- Integrated product teams (IPTs)

4.5. Situational Awareness

Lt Col Andrew D. Woodrow, USAF, BSC

So the crew fly on with no thought that they are in motion. Like night over the sea, they are very far from the earth, from towns, from trees. The motors fill the lighted chamber with a quiver that changes its substance. The clock ticks on. The dials, the radio lamps, the various hands and needles go through their invisible alchemy. From second to second these mysterious stirrings, a few muffled words, a concentrated tenseness, contribute to the end result. And when the hour is at hand the pilot might glue his forehead to the window with perfect assurance. Out of oblivion the gold has been smelted; there it gleams in the lights of the airport. (Antoine De Saint-Exupery)

4.5.1. Introduction to Situational Awareness

From the earliest cockpits fitted with rudimentary gauges to the 5th generation airframes wired for helmet-mounted displays, the impetus for developing an operational philosophy rooted to situational awareness has been grounded on human capacity to process environmental cues, the limits of which provide a continual challenge for engineers and operators. The concepts encompassing the term "**situational awareness" (SA)** are broad, but the reader may benefit by the following definition as a starting point in the understanding of SA:

> "The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future."

The context of SA can be further divided into areas of geographical SA, spatial/temporal SA, system SA, environmental SA, and tactical SA; each subarea identifies the conditions and dynamic flow of activities within a period of time. The linkage between the elements is really a series of sampling from long-term memory concerning relative priorities and the frequency with which information changes, again all linked to perception. Safety analysis from the USAF Safety Center and the National Transportation Safety Board (NTSB) consistently shows two major contributing factors in human factors accidents: operational errors and decision/judgment errors. Elements of the errors include pilot skill deficiencies, task errors, bad decisions, and inadequate planning or situational awareness. Spatial disorientation (SD) is a subset of SA related to the flying environment and is discussed in its own section (section 7.3) under Mission-Imposed Effects (section 7).

4.5.2. Examples of Loss of SA

One of the most significant accidents investigated in the last decade revolved around the loss of SA between the crew and the breakdown in SA between the controller and the crew.

> "On December 20, 1995, about 2142 eastern standard time, American Airlines flight 965, a regularly scheduled passenger flight from Miami, Florida, to Cali,

Colombia, struck trees and then crashed into the side of a mountain near Buga, Colombia, in night, visual meteorological conditions, while descending into the Cali area. The airplane crashed 33 miles northeast of the Cali (CLO) very high frequency omni-directional radio range (VOR) navigation aid. The airplane was destroyed, and all but four of the 163 passengers and crew on board were killed." (NTSB, 1996)

This accident demonstrates the need for training that effectively provides pilots with the ability to recognize when they have lost or have failed to obtain situational awareness. As a result, the NTSB forwarded a recommendation to the FAA to include specific guidance on methods to effectively train pilots to recognize cues that indicate that they have not obtained situational awareness and provide effective measures to obtain or regain that awareness (FAA AC 120-51B).

The focus of most analysis during accident investigation is on determining why higher order skills break down. In one typical example of a USAF mishap, a wide-body, long-haul cargo aircraft missed centerline of the intended runway and subsequently experienced extensive damage to the undercarriage due, in part, to loss of SA. During the approach to the airfield there was very little cockpit conversation, and radio traffic was minimal. The pilot stated it was obvious to her the crew was "tired and just wanted to get on the ground." Joining the crew late in the descent, the jump-seat pilot was cognitively "out of the loop" and made no inputs at all during the mishap. The copilot reached the first segment of the approach 2800 ft too high and 35 kn too fast. Shortly after the point to configure for landing, the crew failed to extend the flaps. The failure to extend the flaps to the landing configuration constituted a significant breakdown in crew communication and situational awareness. It is likely that due to the copilot's nonstandard procedure to initially extend his own flaps, the pilot made the assumption that the copilot would also extend the flaps to landing. While the call was made and confirmed by both pilots, neither pilot actuated the flap handle, nor did either pilot confirm movement or full extension of the flaps.

Within the aviation domain, there are several concepts typically used to characterize performance, but most are difficult to define much less measure. For instance, in the military environment the concept of SA is used frequently to describe skills in maintaining an awareness of the tactical situation. Measure of SA, then, is based on outcome of the tactical objectives. The pathway to the tactical objective is lined with opportunities to sustain, lose, or regain SA. Unfortunately, there are no universally accepted tools to measure SA; the challenging domain for developing validated pilot performance measures remains in the performance outcome mode.

Aircraft ground operations can also be subject to loss of SA as demonstrated in the following excerpt from the NTSB:

"On September 11, 1999, about 1958 central daylight time, a runway incursion involving United Airlines, a Boeing 767, and Delta Air Lines flight 1211, a Boeing 727, occurred at Chicago O'Hare International Airport (ORD), Chicago, Illinois. UAL2, which was being repositioned on the airport by two UAL mechanics, crossed runway 9L without air traffic control (ATC) clearance. DAL1211, which was departing from runway 9L at the time, passed directly over UAL2 at an altitude of 200 to 300 feet. The incident occurred in darkness under visual meteorological conditions. Neither airplane was damaged, and no injuries were reported. The mechanic who was taxiing UAL2 stated that he was looking for a

sign identifying taxiway H. Both crewmembers stated that the area was very dark and that they did not see any signs or lights identifying taxiway H. Thus, the absence of appropriate signage and markings at the runway 32R/taxiway H intersection apparently contributed to the loss of situational awareness experienced by the UAL2 crew, causing them to miss the turn onto taxiway H." (NTSB, April 24, 2000)

Detection and correction of such problems are important because, especially in unfamiliar situations, flight and ground crews depend on proper signs and surface markings to maintain situational awareness and avoid runway incursions.

The rapid growth of technology in the cockpit and aeronautical systems in general along with broadened operational roles is well known in aviation. Analytical operations by resource-limited operators are strained under the best conditions. It could be argued that even basic flight control under instrument meteorological conditions (IMC) involves analytical processing that will overwhelm situational awareness of the most seasoned aviator. It is well accepted that humans are not reliable monitors. To maintain situational awareness, the human operator needs to have an active role in the control loop. That said, the aim of any systems designer or even trainer should be for an internal (healthy) versus external (unhealthy) locus of control (Jensen, 1989). In addition, according to Arrabito, ensuring such cognitive compatibility as a function of situational awareness in the design of an alerting system may minimize the perceptual demand required for interpretation, thereby reducing the possibility of inappropriate responses under stress (Arrabito et al., 2004). Evaluating the cognitive compatibility of an alerting system as a function of situational awareness in an operational setting may not be practical. Under normal flying conditions, auditory alarms are sounded infrequently, and many flights are completed without an alarm being triggered. Likewise, incorporating the signals in simulators may not elicit the same response as would be expected in actual flight. Incorporating situational awareness in the design of an alerting system is expected to increase warning compliance. Such thoughtful auditory alarm design should elicit the operator's attention and appropriate response, particularly under conditions of varying cognitive demands on aircrew. Indeed, human intelligence seems to be an essential requirement for successful performance on real-time dynamic problem-solving tasks.

Situational awareness is not a structure or "thing" that people possess. It is a dynamic process that is the result of cues both presented and perceived. Cues are typically channeled through the physiological sensory systems: visual, tactile, aural, olfactory, and even taste receptors. In the flight environment this cueing might consist of overt signals like a flashing warning light accompanied by an aural tone. In other circumstances the cues may be more subtle, a stick-shaker warning of a stall condition for instance. The distance and timeliness of the signal presentation influence the speed and accuracy of response by the operator. In the operational realm of remotely operated vehicles, the pilot may be thousands of miles away from the vehicle being operated with no direct signals perceived. If the only signal presented to support the pilot's SA is a string of data displayed on one of three monitors, the signal must be compelling enough to gain and hold the attention of the pilot and guide or direct to an action point. As described by Endsley (1988), system sensors collect some subset of all available information from the system's environment and internal system parameters. Of all the data the system possesses, some portion (determined by the designer) is displayed to the operator via its user interface. Of this subset, the operator perceives

and interprets some portion, resulting in situational awareness. A complex process is further complicated by the condition and motivation of the operator. The introduction of the “glass” cockpit and the third-generation airliner in the 1990s represented a significant change to the flight crew (from three to two) by automating many of the functions formerly managed by the flight engineer. Boeing states that the design has reduced the number of cockpit lights, gauges, and switches from more than 970 in the basic B-747 to only 365 in the B-747-400 (Wells, 2001). Good design and training have relieved pilots from many monotonous tasks of monitoring and freed them up for more cognitive tasks that are still beyond the capacity of computers. But has the reduction in workload increased the level of SA in the cockpit?

Approaches and landings at wrong airports are instances of disorientation and loss of SA on the part of the pilot. Most will agree that a discussion of spatial disorientation cannot exclude situational awareness as a component. Extensive literature exists on spatial disorientation in both clinical and aviation studies but rarely relates to way-finding. In the medical literature, topographical disorientation, a specific instance of spatial disorientation, is a term that relates to way-finding problems and focuses on patients. In aviation, way-finding problems have been termed geographical disorientation. In a study by De Voogt (2007), the analysis of accident and incident reports led to insight into situational awareness problems of pilots. The pilot-navigator has to perform two tasks, known as local guidance or staying on a particular flight path and global awareness or knowing where things are with respect to one’s position and orientation. Landings and approaches to wrong airports refer to the latter. In other words, pilots may be in control of the aircraft and may conduct a well-executed landing or approach, but without being aware of the identity of the airport. Alternatively, distraction from good SA can result in loss of control. On December 29, 1972, an Eastern Airlines Lockheed Tristar crashed into the Everglades, killing 100 of 176 people aboard. In the darkness, the crew, preoccupied with a landing gear problem, failed to notice the autopilot had become disengaged and the plane was losing altitude (Fig. 4.5.2-1).

Figure 4.5.2-1. Loss of Situational Awareness

4.5.3. Modeling of SA

One of the popular theories underpinning SA is the mapping or modeling a human does when executing a task. The mental model developed in humans when approaching a series of tasks is a popular means of evaluating situational awareness. A well-developed mental model provides knowledge of the relevant parts of an operation and a means of integrating the elements to some level of understanding that leads to the ability to project future states of the system based on a snapshot of the current state and individual understanding of the system dynamics. The leading theory that explains this multitiered SA model is by Endsley (Fig. 4.5.3-1).

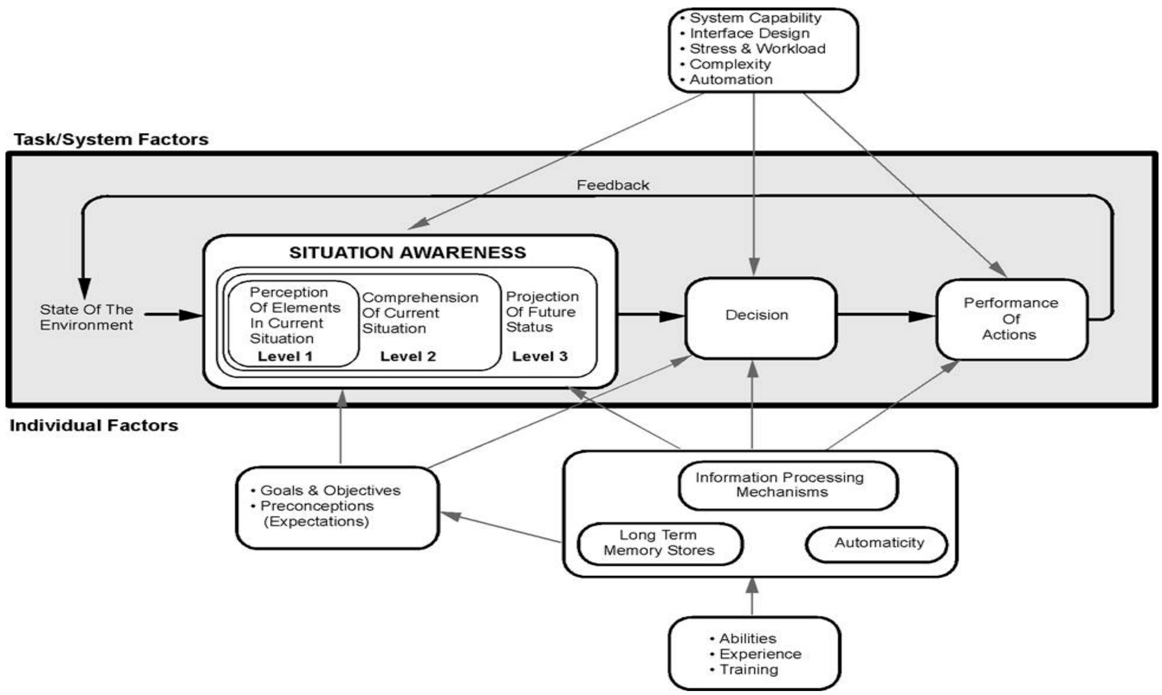

Figure 4.5.3-1. Model of Situational Awareness Depicting the Levels of SA and Interaction between Environmental and Human Factors (Endsley, 1995).

The dynamic nature of the aviation environment (including air traffic control, aircraft marshalling duties, and systems maintenance) causes variations in the level of SA one possesses in a single period of time. The mental model is often referred to as a bucket of resources that is sampled as necessary. For instance, the air traffic controller must maintain an efficient mental model of the control area of responsibility combined with a rapid retrieval system for applying the knowledge of other important cues when needed. As described by Redding in *Aviation Psychology in Practice* (Johnston et al., 1997), the mental model provides a framework for more efficient training and learning, forming the basis for teaching knowledge and skills. Based on the mental model, controller procedures should be taught by event type, with training emphasizing the integration of sector aircraft information into sector relevant groupings.

Expectations of the status of a system are crucially important to perception and sustaining SA. The main function of expectation is to allow more efficient processing of information presented. For instance, try to recall word-for-word a conversation you have had with someone in the last 24 hr. Although it will be relatively easy to recount the general sense of the conversation, the precise words used will likely be forgotten. In

aviation, this becomes dangerous when there is a clear expectation as to exactly what should have been transmitted or displayed, but the operator will remember what was expected rather than the actual transmission. Because it is easy to remember the general sense of something, while forgetting the particulars, checklists are the mainstay of flight deck operations. Human memory is most fragile when there are stresses upon the physiological or psychological state of the operator. If one considers all of the information stored in long-term memory relevant to a particular task, it is easy to map out the location of “sector-relevant” information. For instance, consider driving a car on a familiar highway versus through a busy, unfamiliar downtown grid. In the first instance, many of the individual SA resources used for navigation, speed control, and eye-hand coordination can be given up for other, nondriving-related tasks like reviewing the shopping list, talking on the cell phone, or any one of a dozen other tasks. Compare that to the SA resources expended when navigating through a busy network of streets while searching for an unfamiliar address—clearly fewer resources are available for extraneous duties. Any technique for enhancing the amount of relevant information we perceive has to take account of the fact that visual cues are not enough; the driver must systematically look for something specific. This means that there is a link between learning the skill of driving well and learning to apply your vision to the things you need to see. In the driving example, there are fewer categories of things that need to be viewed than in aviation. Nevertheless, the store of knowledge still needs to be vast. Therefore, developing a scanning technique must be linked to the elements of thinking and anticipating effectively. Once basic skills sets are established and the SA “bubble” is expanded from a baseline, learning operations theory and applying skills through practical experience are required for an increase in risk perception. As driver training instructors in the United Kingdom harp to their students—“Mirror, Signal, Maneuver!”—the way to increase the perception of relevant information is to use a scan strategy, not just visually but across the mental model. Developing a systematized way of perceiving information in the environment elicits a regular sampling process without having to consider what to do first. This is particularly true during a single-seat aircraft emergency.

- Fly the airplane.
- Evaluate the proper action/checklist needed.
- Continue to fly the airplane and take the appropriate action/s.

This changes with a multiplace aircraft where the copilot is usually instructed to fly the airplane while the aircraft commander directs the emergency response while cross-checking that the aircraft is really being flown. Too often, the emergency occupies 100% of the pilot’s awareness, the result being loss of aircraft control unrelated to the particular emergency condition.

It could be argued that, with practice, the resources required to maintain control in the most cognitively demanding situations can be titrated efficiently to a successful outcome. The cognitive constructs and processes thought to underpin the SA process have received great attention by organizational and aviation psychology and now human factors engineers.

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Concepts

Situational awareness (SA)

Vocabulary

Instrument meteorological conditions (IMC)

5. AIRCRAFT SYSTEMS EFFECTS

5.1. Pressurization Systems

James T. Webb, Ph.D.

5.1.1. Cabin Pressurization

Cabin pressurization is an increased atmospheric pressure in an aircraft cabin or cockpit. The increased pressure is maintained by pumping pressurized, conditioned air into the cabin from one or more jet engine compressors or an aircraft-powered electronic compressor. In transport and commercial aircraft, cabin pressurization usually keeps the cabin no higher than 8000 ft. In fighter and most training aircraft, the cockpit pressure is dependent on the aircraft altitude and typically exceeds 10,000 ft, requiring supplemental oxygen.

During WWII, the problems of hypoxia, hypothermia, and altitude decompression sickness (DCS) plagued operators of the unpressurized B-17s and B-24s. The cabin pressurization designed for the B-29 provided a solution to these problems. Since that time, nearly all U.S. military aircraft capable of flight above 20,000 ft have been designed with pressurized cabins for the same reasons. The CV-22 is one notable exception.

5.1.2. Physiologic Requirements of Pressurized Cabins

Unpressurized aircraft could expose crew and passengers to an unacceptable level of hypoxia if altitude limitations were not imposed. The Federal Aviation Administration (FAA) and other regulatory authorities limit exposure altitudes for unpressurized aircraft and pressurized aircraft that lose pressurization. Those regulations stipulate that crewmembers must not be exposed to altitudes above 10,000 ft and passengers not above 12,000 ft without supplemental oxygen. The altitude allowed for crewmembers may be lowered at night due to the effects of hypoxia on night vision.

Cabin pressurization allows a “shirt sleeve” environment for crew and passengers of transport and commercial aircraft. Keeping the cabin pressure to less than 10,000 ft, 8,000 ft in most military transport aircraft and 6,000 to 8,000 ft in commercial aircraft, eliminates the problem of DCS and minimizes loss of function due to hypoxia . At 8,000 ft (Appendix 1a) the PAo_2 (calculated) of 69 mmHg provides an arterial oxygen saturation of 87%-95% during rest. This level of oxygenation ensures adequate cognitive performance and reasonable physical capabilities; although some prolongation of reaction times to accomplish previously unlearned tasks has been reported (Denison et al., 1966). These results were obtained with the source of pressurization being atmospheric air (21% oxygen). Crewmembers that are more physically active will experience some reduction in physical and cognitive performance due to the increased oxygen demand associated with mild to moderate exercise at 8,000 ft (Macmillan, 2006).

5.1.3. Physical Limitations of Aircraft Pressurization Systems

The aircraft skin must be stronger for higher differential pressures to be maintained. This adds weight to the aircraft and increases the stress on the skin and fuselage during repeated applications of the differential pressure. Thus, in addition to more bleed air or compressed air required to supply the cabin, further reducing aircraft engine efficiency, maintaining a higher differential represents a physical limitation.

5.1.4. Types of Aircraft Pressurization Systems

As shown in Figures 5.1.4-1a and b, hot, pressurized air from the engine compressor or an air intake port is allowed to decompress and cool (adiabatic cooling and refrigeration) to the desired cabin inlet pressure and temperature to maintain the desired cabin environment. An outflow valve controls the pressure by modulating the rate of porting air overboard and is, in turn, controlled in the cockpit by the crew. The engineer (crewmember) of transport and commercial aircraft normally sets automatic controls, which pressurize the cabin to the desired cabin pressure, typically 6,000 to 8,000 ft. This ensures a smooth cabin depressurization to that altitude, and then maintaining whatever differential pressure with the ambient (outside, atmospheric) pressure is necessary. On descent, the same cabin altitude controller adds pressure to the cabin to pressurize it to the destination field pressure altitude. Fighter and most 2-place trainer aircraft usually follow an automatic pressurization schedule such as shown in Figure 5.1.5-1.

The pressurization sometimes felt at ground level when the doors of a commercial aircraft are closed is the cabin air conditioning system adding a small amount of pressurization. The cabin air-conditioning system is part of the cabin pressurization system (environmental control system) and derives its air source from the aircraft engines or a ground air cart. When the doors close, the air supplied does not have as many openings to depart the aircraft, hence a slight increase in pressure. As a commercial or military transport aircraft takes off, two processes are occurring at the same time. The aircraft is being decompressed by ascending to altitude just as your car would be if you drove up to the top of Pikes Peak, only faster. At the same time, the cabin altitude controller is attempting to keep the aircraft cabin from ascending above about 8,000 ft (typical cabin altitude during flight above 8,000 ft) as the aircraft passes that altitude. Your car doesn't have that option. Therefore, during ascent the cabin altitude controller begins pumping air into the cabin. The amount of air pumped in is regulated by an outflow valve. During descent from cruise altitude, e.g. 35,000 ft, the cabin altitude controller adds more air to the cabin to bring it down from 8,000 ft to sea level (assume you are landing at Honolulu International) in a smooth, slow recompression. The cabin altitude controller actually starts to recompress the cabin well above 8,000 ft so that the descent, repressurization, of the cabin occurs more slowly than if it waited until the aircraft passes 8,000 ft during descent, making it easier for passengers to clear their ears.

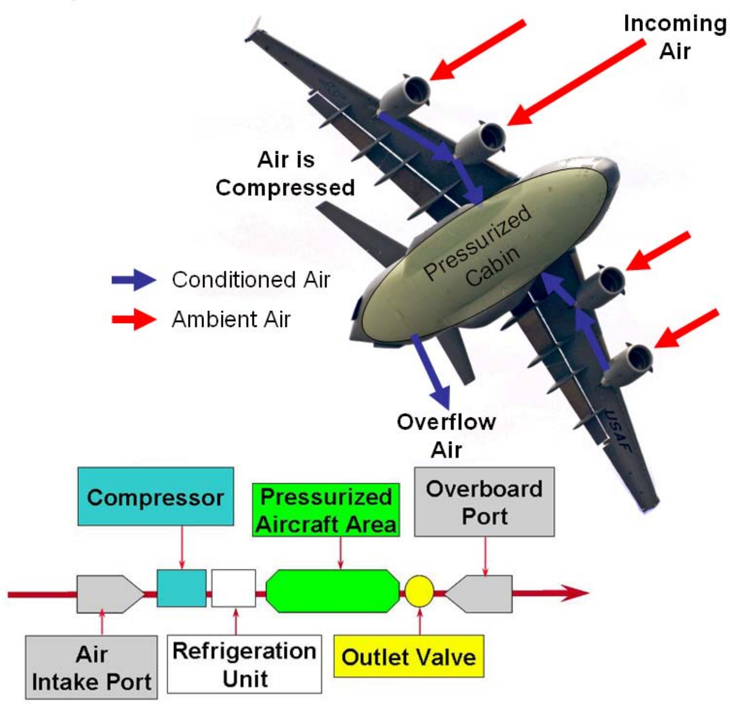

Figure 5.1.4-1a. Aircraft Pressurization System – Engine Source

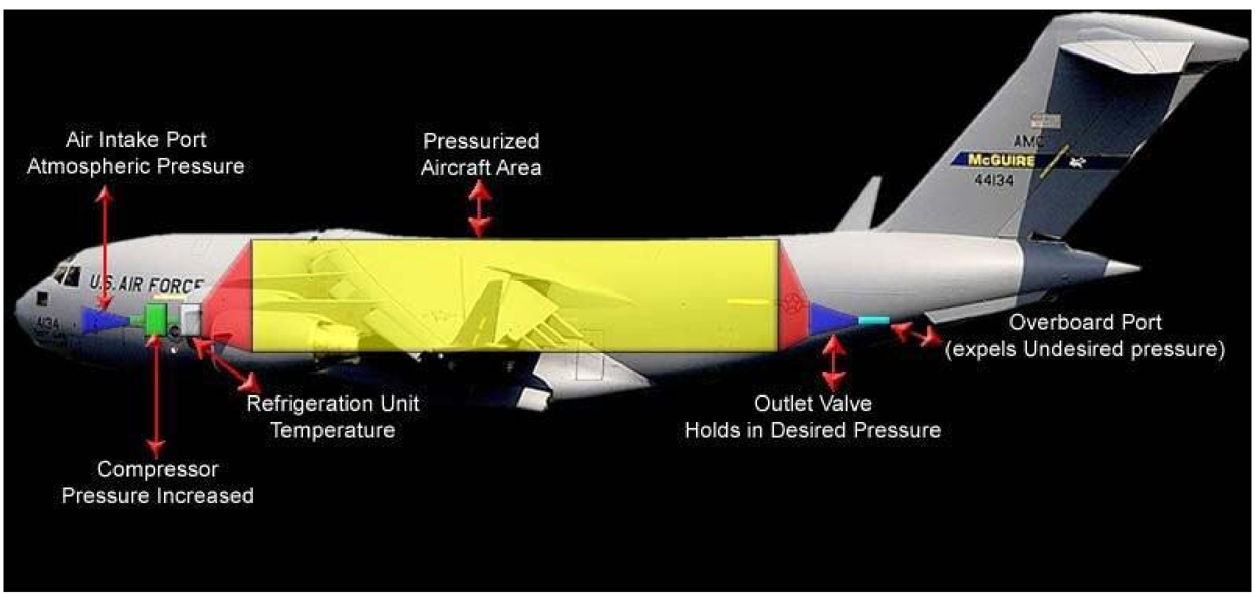

Figure 5.1.4-1b. Aircraft Pressurization System – Air Intake Port Source

5.1.5. Aircraft Pressurization Schedules

A pressurization schedule is defined as the relationship between cabin altitude and aircraft altitude. Transport aircraft that routinely carry passengers have pressurization schedules that create a high differential pressure between the cabin and aircraft altitude to maintain passenger comfort. With the high differential pressure, the cabin can be maintained below 10,000 ft where supplemental oxygen (oxygen mask) is not required. Most military transport aircraft and commercial aircraft maintain a cabin

altitude of 6,000 or 8,000 ft called an isobaric pressurization system. They can manually depressurize and repressurize to accommodate the mission scenario, e.g., air drop. These aircraft cabins decompress during the climb from ground level to 8,000 ft and then supply pressure to maintain 8,000 ft during further climb.

Fighter and some other military aircraft are not pressurized until they reach 8,000 ft, where the pressurization system maintains 8,000 ft, isobaric, until the aircraft reaches about 23,000 ft. At that altitude, 5.0 psid (differential pressure) exists between the cabin and ambient (outside) air. This type of pressurization system is, therefore, called an isobaric differential pressurization system.

The 5 psid with ambient pressure is maintained by the system during any remaining climb as shown in Figure 5.1.5-1. For aircraft with a 5-psid pressurization system capable of cruise at altitudes greater than 50,000 ft, the cockpit altitude will exceed 20,000 ft. Oxygen masks are worn at all times in such aircraft, and their oxygen regulators provide adequate supplemental oxygen to keep the pilots from experiencing hypoxia. At 70,000 ft aircraft altitude, the cabin of an aircraft with a 5-psid pressurization system would be at nearly 25,000 ft. This represents an exposure consistent with development of DCS during more than 5% of the exposures even with no physical activity if the time at 70,000 ft exceeds about 1 hr.

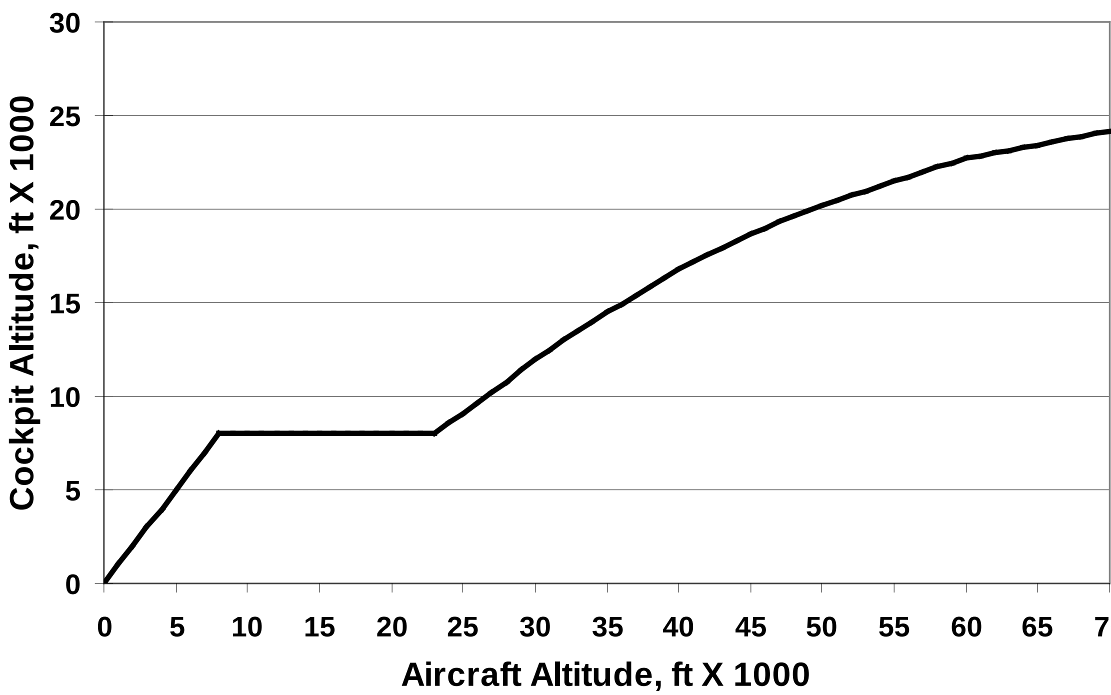

Figure 5.1.5-1. 5-psid Cockpit Pressurization Schedule

5.1.6. Advantages and Disadvantages of Pressurized Cabins

There are several advantages of a transport aircraft cabin pressurized to 8,000 ft.

1. Hypoxia and DCS are avoided without the use of supplemental oxygen and/or pressure garments.
2. Avoidance of hypoxia and DCS allows better utilization of crew and improved crew safety, leading to higher rates of successful mission completion.

3. Functional temperature control associated with cabin pressurization provides a shirt-sleeve environment for passengers and crew to perform their duties, thus enhancing performance and mobility while reducing fatigue.

Pressurized fighter aircraft cockpits are not sufficiently pressurized to prevent hypoxia while at aircraft altitudes exceeding about 25,000 ft without supplemental oxygen. Routine use of a helmet and mask connected to the oxygen regulator is required in these aircraft to prevent hypoxia.

Some transport aircraft such as the C-5 maintain atmospheric pressure, 14.7 psia at sea level, during the climb to 14,000 ft. At 14,000 ft and above, the C-5 maintains an 8.7 psid between internal cabin and external atmospheric pressure. This ensures that even at an aircraft altitude of 40,000 ft, the C-5 cabin would be below 7,000 ft pressure equivalent (8.7 psid + 2.7 psi at 4,000 ft = 11.4 psi, 6,900 ft).

Other aircraft have pressurization schedules that require supplemental oxygen while the aircraft is at high altitude. The U-2 cabin pressure is approx 29,500 ft at cruise altitude, which is normoxic. The helmet regulator supplies 0.8 to 1.4 in. of water pressure to the face cavity at all altitudes. This small overpressure ensures a seal is maintained between the face area and the suit area, preventing hypoxia and the possibility of leaks during denitrogenation.

The disadvantages of pressurized cabins are:

1. Most aircraft pressurization systems use bleed air from the engine compressor as a source of compressed air. This reduces engine efficiency. Compressors used on other aircraft require an energy source, which also reduces overall efficiency since electricity or hydraulics to run the compressors ultimately derive their power from the engines. The weight of these systems is added to the aircraft weight, which further reduces efficiency.
2. The differential pressure between the ambient aircraft altitude and the cabin altitude creates a stress on aircraft structures that reduces the life of the airframe, in particular, the aircraft skin covering the fuselage.
3. The initial cost of cabin pressurization systems is also a disadvantage, as it raises the total cost of the aircraft.
4. Loss of cabin pressure in a pressurized cabin creates a need for reduction in aircraft altitude to avoid hypoxic conditions and usually involves thermal stress for the occupants.
5. The reduction in altitude reduces efficiency in converting fuel to miles traveled.
6. A potential loss of efficiency makes maintenance of pressurization systems a priority, which uses time and materials (money) in addition to the initial cost of the systems. Loss of cabin pressure in U.S. military aircraft was reviewed by Files et al. (2005), providing a summary of the many possible physiologic outcomes.

5.1.7. Factors Affecting the Rate and Severity of a Decompression

The rate of the decompression refers to the speed at which the decompression occurs. It is determined by a number of factors. Some of these factors are determined by the reason for the decompression. Is it a mechanical failure of the pressurization system, in which rate of decompression is limited to the rate of altitude change of the aircraft? Is it an aircraft structural failure (hole in the aircraft skin or loss of a hatch, window, or canopy), in which rate of decompression is dependent on the size of the

failed area? Or is it an operator error? An error in operation of the pressurization system can usually be corrected before complete decompression occurs. However, if the error involves inadvertent actuation of an irreversible decompression control, decompression can be very rapid. If the depressurization is very slow, the cabin pressurization system may be able to make up for the rate of loss of air. The following factors apply to determining rate of decompression:

1. How big is the cabin? Usually, a large cabin will take longer to depressurize than a small one.
2. How big is the aperture causing the decompression (see Figure 5.1.7-1)? The bigger the hole, the faster the decompression.
3. What is the pressure ratio between the cabin and the ambient (outside) pressure before the decompression begins? The larger the ratio, the longer the decompression duration.
4. What was the pressure differential prior to the decompression? The severity of the decompression is determined by the differential pressure, and a higher differential pressure results in a faster initial rate of decompression.
5. What is the altitude at the time of decompression? The altitude at which the decompression occurs will affect the pressure ratio and the pressure differential. This is important due to the rate of onset of physiologic problems associated with decompression, the most important of which is hypoxia.

Equations exist to determine the rate of a decompression, taking these factors into consideration.

Figure 5.1.7-1. Aloha Airlines Decompression Disaster

5.1.8. Physical Indications of a Rapid Decompression

A rate of decompression described as rapid, 2-15 s, will be accompanied by several physical indications. It usually coincides with a loud noise closely followed by a drop in cabin temperature. The temperature drops due to adiabatic cooling associated with expanding air as well as equilibration with the ambient temperature at the aircraft altitude. The actual pressure drop may also be felt as trapped gas in the body expands. Light debris may accompany the rush of air moving toward the source of the decompression, and objects not secured and near the aperture may depart the aircraft. Based on the pressure and temperature drop, the relative humidity may reach 100%, resulting in fog, another physical indication of a rapid decompression.

5.1.9. Physiologic Effects of Decompression

Any decompression carries some risk of trapped gas expansion; the degree is a function of initial and final pressures. Decompression to above 10,000 ft altitude carries an additional risk of hypoxia, although proper use of oxygen equipment will usually eliminate the effects until appropriate repressurization/descent can be accomplished. The exception is rapid decompression to an altitude where onset of hypoxia is rapid and severe, as discussed in the section on hypoxia. A slow decompression, once recognized, carries less risk of hypoxia due to the ability to take corrective actions, including donning of oxygen masks. However, recognition of the decompression may be a factor depending on the type and function of warning devices in the aircraft and their interpretation by aircrew. Hypoxia symptoms develop insidiously in a slow decompression, progressively degrading the crewmembers' ability to recognize the decompression and respond accordingly, hence providing a more dangerous situation.

DCS is usually not a factor if an immediate descent is accomplished to below 10,000 ft. If a higher altitude level off is necessary or descent is delayed, DCS must be considered an additional risk, and appropriate and available DCS treatment must be considered when determining where to land.

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Recommended Reading

Davis JR, Johnson R, Stepanek J, Fogarty JA, Eds. Fundamentals of Aerospace Medicine. 4th Ed. Lippincott Williams & Wilkins. 2008.

Concepts

- Cabin pressurization
- Pressurization schedule
- Rate of decompression

Vocabulary

- Rapid decompression (RD)

5.2. Oxygen Systems

Maj Steven W. Dawson, USAF, BSC and Mr. George Miller

5.2.1. Introduction

Aircraft oxygen systems are fundamental components to all manned aircraft. Even in the most advanced aircraft, slight flaws in oxygen systems design can result in catastrophic mishaps. Careful consideration is necessary to cover the full envelope of today's advance aircraft capabilities, to include normal flight operations as well as emergencies. In addition to aircraft design considerations, aircrew members must have a thorough understanding of the equipment necessary to operate in oxygen deficient environments.

In the early days of aviation, oxygen systems provided very limited and inefficient protection. For instance, the "pipe stem" oxygen system required the aviator to maintain the pipe stem between his teeth. This and other early systems used a continuous flow design, which wasted oxygen.

As aircraft became more complex, so did oxygen systems. Designers began to recognize that physiological requirements were based upon a wide variety of factors, including workload, altitude, acceleration, temperature, and physiological stresses. In addition, designers recognized the need for more efficient delivery systems.

Advancements in oxygen systems are based upon those physiological factors. These systems enable higher altitude flights, more efficient oxygen utilization, and more efficient storage. "Demand" oxygen systems, for instance, not only provided for more efficient oxygen utilization but for protection against exposure to higher altitudes. Further development of "pressure-demand" systems led to automatic capabilities for altitude protection: <u>pressure breathing for altitude (PBA</u>) and acceleration protection <u>pressure breathing for G (PBG)</u>. In terms of oxygen delivery, the ability to generate oxygen on board the aircraft provided for smaller storage capability and reduced logistical burden.

Even today, challenges exist in designing and updating aircraft oxygen systems to cover advanced capabilities while considering the myriad of logistical concerns associated with aircraft engineering constraints.

5.2.2. Standard Components of Oxygen Systems

Aircraft oxygen systems generally consist of four core components:

a. Oxygen storage system or onboard oxygen generating system (OBOGS)
b. Tubing to flow oxygen from the supply source to a regulator(s)
c. Regulator for controlling the oxygen pressure delivered to the user and, in some cases, the oxygen concentration delivered
d. Oxygen mask and connector to provide oxygen to the lungs

5.2.3. Oxygen Storage Systems

With any oxygen system, several safety guidelines are pertinent to protect the user from the danger presented by the capability of 100% oxygen to greatly increase fire hazards. The use of high-pressure systems also presents explosive effects, which

must be recognized. Safety procedures for handling and storage of the various types of oxygen equipment and supplies are found in T.O. 15X-1-1 and in aircraft flight manuals.

5.2.3.1 Gaseous Oxygen. Aviator's breathing gaseous oxygen is designated Type I per military specification MIL-PRF-27210, AVIATOR'S BREATHING, LIQUID AND GAS. Gaseous oxygen shall contain not less than 99.5% oxygen by volume. The remainder, except for moisture and minor constituents specified in MIL-PRF-27210, shall be argon and nitrogen. It must be odorless and free of toxic contaminants. Moisture shall not exceed 7 ppm of water vapor or a maximum dew point of -82°F. Aviator's oxygen is different from other types of breathing oxygen because it contains lower amounts of water vapor. Although it tends to dehydrate the aircrew member, low moisture content in aviator's oxygen is necessary. At altitude, excessive water vapor could freeze and restrict the oxygen breathing gas. Aircraft gaseous oxygen cylinders are made from shatterproof materials to minimize injury and damage if the cylinder is struck by a ballistic round.

(1) Oxygen Gas – Low Pressure. Aviator's breathing oxygen is stored in yellow, lightweight, non-shatterable cylinders (Fig. 5.2.3-1). These cylinders carry a maximum charge of 450 psi and are normally filled to 450 psi. The low-pressure system reduces the risk of explosions but limits the amount of oxygen available to the aircrew member.

Figure 5.2.3-1. Low-Pressure Oxygen Bottles

The cylinders' duration depends on the altitude and breathing characteristics of the user and the initial charge pressure (see Table 4.1 of T.O. 15X-1-1. The limited volume mandates on-aircraft recharge or immediate descent when the pressure dips below 300 psi. A system that drops below 50 psi must be filled within 2 hr to prevent water vapor entry and condensation; otherwise, it must be purged to eliminate moisture (per T.O. 15X-1-1). Low pressure oxygen cylinders are primarily used during aircraft emergencies.

(2) Oxygen Gas – High Pressure. Some aircraft are equipped with high-pressure cylinders. Most fighters, bombers, and trainers are equipped with high-pressure cylinders used during aircraft emergencies, such as ejection, and are generally mounted on ejection seats. These cylinders are green and carry a maximum charge of 2100 psi and are normally filled to a pressure of 1800-2100 psi. The main advantage of the high-pressure cylinder is the large amount of oxygen stored in a small volume.

5.2.3.2 Liquid Oxygen (LOX). Aviator's breathing gaseous oxygen is designated Type II per military specification MIL-PRF-27210, AVIATOR'S BREATHING, LIQUID AND GAS. Aircraft liquid oxygen systems convert liquid oxygen to gaseous oxygen by allowing the surrounding atmosphere to passively warm the liquid oxygen as it passes from the storage vessel and through a heat exchanger. When LOX is converted to its gaseous state, it expands to about 860 times its original volume[2] (1 L LOX = 860 L of oxygen gas). The expansion ratio of liquid to gaseous oxygen makes it ideal for aircraft use as long as there is a readily available means for LOX refilling capability. Once in gaseous form, the oxygen shall contain not less than 99.5% oxygen by volume. The remainder, except for moisture and minor constituents specified in MIL-PRF-27210, shall be argon and nitrogen. The oxygen shall be free from all contaminants of known toxicity. Like Type I oxygen, it must be odorless, and moisture shall not exceed 7 ppm of water vapor or a maximum dew point of -82°F.

The heart of the liquid oxygen system is a double-walled vacuum insulated container, commonly called a LOX converter (Fig. 5.2.3-2). Connections leading to the inner shell of the container are surrounded by a vacuum space to minimize heat leaks. In filling the system, the pressure buildup and vent valve (a two-position valve) is placed in the VENT position. This allows the flow of liquid into the container and vents container gas pressure to the atmosphere. The filler valve is connected to the liquid oxygen storage tank via an insulated, flexible hose. Pressure in the servicing tank forces liquid oxygen into the aircraft liquid oxygen converter.

Figure 5.2.3-2. Liquid Oxygen Converter

5.2.3.3 Onboard Oxygen Generating System (OBOGS). The OBOGS eliminates the need for a stored oxygen supply by generating oxygen from aircraft engine bleed air. Various types of OBOGS have been developed using different physical and chemical properties; however, the only viable OBOGS for production aircraft uses pressure swing adsorption technology and a molecular sieve adsorbent to concentrate oxygen. Hence, sometimes the OBOGS is called the molecular sieve oxygen generating system (MSOGS). Molecular sieves are synthetically produced zeolites (naturally occuring aluminosilicate minerals), and are characterized by pores and internal cavities of extremely uniform dimensions. These crystalline materials have three-dimensional structures based on silicon oxide ($SiO4$) and aluminum oxide ($AlO4$)

[2] LOX molar density at 1 atm is 35.65 (mol/L) (Perry & Chilton, 1973). Application of the Ideal Gas Law using 1 atm and 70 °F results in 1 L of liquid LOX converting to 860.7 L of gaseous oxygen. T.O. 15-1-1 states the conversion is 862:1.

polyhedra. The polyhedra are linked by their corners to produce an open structure with internal cavities in which molecules can be trapped. These materials are engineered so that access to the internal cavities is through specific and uniform sized pores (Sigma-Aldrich). The molecular sieve adsorbs the nitrogen in the bleed air, thereby producing an oxygen-rich breathing gas. As long as engine bleed air at sufficient pressure is available, a continual supply of breathing oxygen can be produced. The oxygen is monitored for purity to ensure it meets the minimum physiological requirements based on the cabin altitude. The gas produced is typically in the range of 40%-93% oxygen (Miller, 1994; Miller et al., 1998) depending on operating conditions (i.e., cabin altitude, demand flow, inlet air pressure, etc.). The OBOGS is dependent on engine bleed air pressure, temperature, and quality. Therefore, proper integration of the OBOGS and the engine bleed air system or aircraft environmental control system is critical. Further, emergency oxygen systems are used more frequently on OBOGS-equipped aircraft because engine bleed air pressure reductions or stoppages can occur. Hence, emergency oxygen systems must be properly sized and designed for potential frequent use.

Typically, the MSOGS is composed of two or three beds or canisters of molecular sieve adsorbent, valving, a purge orifice, and an electronic timer. The adsorbent beds are alternately cycled through steps of adsorption and desorption. During adsorption, air at moderate pressure (20-60 psig) enters the adsorbent bed, whereupon nitrogen is preferentially adsorbed and enriched oxygen is recovered from the system’s product port. During pressurization, nitrogen is adsorbed because the molecular sieve has a greater affinity for the nitrogen molecule. This affinity occurs because the nitrogen molecule has a slight polarity. The adsorption step is followed by desorption, or venting, of the adsorbed nitrogen to ambient pressure. Ambient pressure varies with aircraft altitude, and this reduction in pressure at altitude is used to desorb the nitrogen from the molecular sieve. At ambient pressure, the molecular sieve can retain only a small portion of the nitrogen; hence, most nitrogen is released. During the desorption step, a small portion of the product oxygen flows through an orifice to the depressurized bed to purge the remaining nitrogen from the bed. This phase prepares the molecular sieve canister for the next pressurization step. These cycles of adsorption and desorption are repeated, resulting in a stream of enriched oxygen at the outlet of the oxygen concentrator.

The MSOGS is installed in several types of aircraft:

(1) Although most F-16's use LOX, some use MSOGS (Fig. 5.2.3-3). The F-16 MSOGS is designed to run at the highest purity possible based on operating conditions, typically 93%. Oxygen purity is monitored by a zirconium oxygen sensor. The CRU-98, aircrew dilution regulator, dilutes the oxygen with cabin air prior to delivery to the pilot's mask. The system has a regulated emergency oxygen system (REOS) with an aircrew mini-regulator located within the integrated terminal block (ITB).

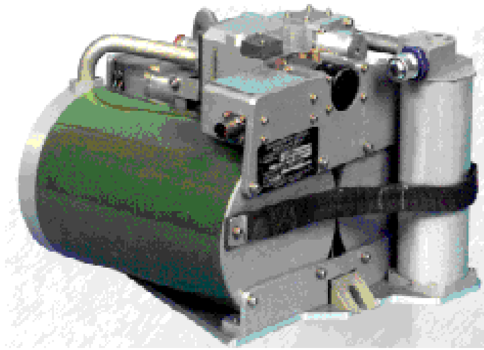

Figure 5.2.3-3. F-16 Oxygen Concentrator

(2) The B-1B MSOGS is composed of a concentrator assembly, a release valve, two purge valves, and four breathing regulators (Fig. 5.2.3-4). The MSOGS is designed to run at the highest purity possible based on operating conditions. The breathing regulators are non-dilution, pressure-demand regulators, qualified to an altitude of 42,000 ft. For this system, automatic pressure breathing begins at 30,000 ft (cabin altitude), which increases to 15-19 mmHg at 45,000 ft. A backup oxygen system (BOS) is automatically activated if cabin altitude exceeds 28,000 ft. The BOS may also be manually activated.

Figure 5.2.3-4. B-1B Oxygen Concentrator

(3) The F-15E MSOGS consists of an oxygen concentrator with an integral self-charging backup oxygen system, zirconium oxygen monitor, and two CRU-98 breathing regulators (Fig. 5.2.3-5). Again, the MSOGS is designed to run at the highest purity possible based on operating conditions. The CRU-98 regulator dilutes the oxygen to that required for the specific cabin altitude. The F-15E MSOGS was qualified to 50,000 ft and was qualified with the combined advanced technology enhanced G ensemble (COMBAT EDGE). The F-15E MSOGS has a self-charging 93% backup oxygen system that only charges when the oxygen concentrator produces ≥93% oxygen. The system provides about 10 min of breathing gas for the two-man aircrew on the ground and a greater duration at altitude.

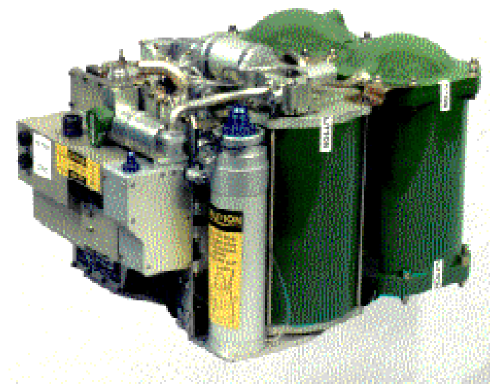

Figure 5.2.3-5. F-15E Oxygen Concentrator

(4) The F-22 MSOGS uses an oxygen concentrator that has three molecular sieve canisters loaded with molecular sieve adsorbent. A zirconium oxygen sensor monitors oxygen concentration of the product gas. The MSOGS controls the oxygen concentration of the product gas based on the cabin altitude. The F-22 uses a nondilution breathing regulator. This system has a seat-mounted, manually activated REOS. If the cabin altitude reaches 25,000 ft, an automatic warning signal is issued, requiring the pilot to manually activate the REOS. The REOS is automatically activated during the ejection sequence.

5.2.4. Tubing to Conduct the Oxygen from the Supply Source to a Regulator

The plumbing of an oxygen system consists of valves, tubing, and fittings.

5.2.4.1 Valves. Valves regulate the flow, pressure, or direction of oxygen. Valves can be activated manually, electronically, or pneumatically. Check valves are installed to permit flow of oxygen in one direction only. Valves can prevent loss of the oxygen supply in the event a component develops a leak. Various styles of single, dual, and triple check valves are available. The direction of oxygen flow is indicated by an arrow that is molded or stamped on the casing.

Pressure-regulating valves are installed in aircraft and altitude chambers to maintain oxygen pressure at a prescribed level. Some oxygen breathing regulators are designed to operate at a 70-psi pressure, thus requiring pressure-regulating valves upstream to reduce the oxygen supply pressure.

On-off valves are installed to control the flow of oxygen.

5.2.4.2 Tubing. Tubing refers to the interconnecting piping between the components of the system. Distribution lines are different for high-pressure and low-pressure lines. High-pressure lines can be copper or stainless steel. Low-pressure lines can be aluminum alloy.

Oxygen tubing and equipment should be designed to ensure that at least a 2-in. clearance exists between oxygen system components and control cables or other moving parts of the aircraft. To maintain this clearance, oxygen tubing will be bent or rerouted. It is desirable to maintain a 6-in. clearance between oxygen tubing and electrical wires. If this is not possible, wires must be covered with additional electrical insulating material and clamped so the wires cannot come closer than 0.5 in. to oxygen tubing.

These separation requirements don't apply where barriers such as frames, ribs, or permanent partitions exist between oxygen tubing and electrical wiring or where electrical wiring is leading into oxygen equipment.

In routing the tubing, the general policy is to keep the total length to a minimum. A shallow bend or dip should be placed in each tubing length to allow for expansion and contraction, vibration, and fittings. Tubing shall be installed so no part of it is in close proximity to fuel, oil, or hydraulic systems. Flares, bends, and connections must be made correctly to ensure the integrity of the oxygen system.

5.2.4.3 Fittings. Types of fittings include connectors, nipples, elbows, and couplings necessary to connect the tubing to the components of the system. Fittings used on oxygen systems are usually aluminum alloy, stainless steel, or copper alloy. Straight thread, gasket, or O-ring seal fittings are not generally used because of the possibility of leakage at low temperatures. Cast brass fittings aren't used because of their porosity. Fittings in aircraft and altitude chamber systems typically have flared end fittings. When pipe thread fittings are used, Teflon tape is applied to seal the fittings. The tape must not extend beyond the first thread to avoid the risk of tape entering the fitting. Teflon tape is not used on flare fittings.

5.2.5. Regulators

Regulators govern the flow and pressure of oxygen to the aircrew member. Oxygen regulators have advanced significantly over the years. Early oxygen regulators provided a continuous flow of oxygen. These types of regulators were not very efficient because oxygen was wasted. In addition, they were insufficient for some flight parameters. The next generation of regulators, diluter demand, offered the capability of oxygen dilution to improve the efficiency of oxygen use. Pressure-demand regulators added a pressure breathing capability, allowing aircrews to reach even greater altitudes.

5.2.5.1 Continuous Flow Regulators*.* As the name suggests, <u>continuous flow regulators</u> provide a continuous flow of oxygen to the oxygen mask. Continuous flow regulators are used on civilian transport type aircraft and on some military aircraft for decompression emergencies. These systems provide a get-me-down capability up to a maximum emergency altitude of 40,000 ft. Oxygen is normally supplied via storage containers in high- or low-pressure gaseous form. These systems may be stationary or portable and may be automatically or manually activated.

5.2.5.2 Diluter-Demand Regulators. These regulators supply oxygen upon demand (inhalation). Inhalation develops a slight negative pressure on the mask side of the regulator and allows oxygen to enter. Normally the system dilutes oxygen with ambient air at altitudes up to 34,000 feet. The system delivers enough oxygen for altitudes up to 35,000 feet.

5.2.5.3 Pressure-Demand Regulators. Continuous flow or diluter demand oxygen regulators may not provide enough oxygen above 35,000 ft, even with 100% oxygen. With a pressure-demand system, 100% oxygen can be delivered at pressures higher than the ambient pressure, thereby increasing the partial pressure of oxygen in the lungs. Pressure breathing provides sufficient oxygen breathing pressures during emergencies at high cabin altitudes. Various types of pressure-demand regulators may be found in today's aircraft.

(1) CRU-73/A Oxygen Regulator and CRU-92/A Oxygen Regulator. The CRU-73/A is a narrow, panel-mounted regulator often used in altitude chambers, as well as various fighter, cargo, and bomber aircraft (Fig. 5.2.5-1). The inlet pressure of the CRU-73/A regulator is typically about 70 psi. The CRU-92/A is similar to the CRU-73/A but has a night vision light plate.
The following controls and indicators are located on the front panel of the regulator and are typical of most oxygen pressure-demand regulators (Fig. 5.2.5-1):

Figure 5.2.5-1. CRU-73/A Regulator

Pressure Gauge – The pressure gauge is found on the upper right of the panel and indicates inlet pressure to the regulator. The gauge displays the amount of oxygen pressure present in the system in pounds per square inch (psi).

Oxygen Flow Indicator – The window area on the left side of the panel marked FLOW indicates the flow of oxygen through the regulator by a visible blinking action. The flow indicator blinks or shows white during inhalation.

Control Levers – The regulator has three control levers:

- The SUPPLY control lever, located on the lower right corner, controls the supply of oxygen.

- The DILUTER control lever, located on the lower center of the panel, has two positions: 100% and NORMAL. Oxygen is mixed with ambient air when the control lever is set to NORMAL. Inhalation causes the soft diaphragm to open and deliver a small amount of 100% oxygen. The regulator senses cabin altitude and provides the proper percentage of oxygen, ultimately achieving 100% oxygen (above 32,000 ft).

- The EMERGENCY PRESSURE control lever, located on the lower left of the panel, has three positions: EMERGENCY, NORMAL, and TEST MASK. In the EMERGENCY position, the regulator delivers positive pressure (at altitudes when positive pressure is not automatically delivered). In the NORMAL position, the regulator operates by providing flow when demanded by the user. In the TEST MASK position, oxygen is delivered to the mask under increased pressure and may used for checking the seal of the mask.

(2) CRU-68/A Oxygen Regulator. The CRU-68/A oxygen regulator is a narrow, panel-mounted regulator and, though mostly obsolete, may still be found in USAF aircraft (Fig. 5.2.5-2). It doesn't incorporate an "off" warning for the oxygen supply, which could result in aircrew members inadvertently flying without an oxygen source.

Figure 5.2.5-2. CRU-68/A Regulator

(3) The T-6 oxygen regulator (Figure 5.2.5-3) is installed on the right side console in the T-6 cockpit. Each regulator has a supply lever, a concentration lever, a pressure lever, a built in test (BIT) button, a flow indicator (blinker), and a maximum concentration flow light. Each regulator panel controls OBOGS electrical power and oxygen flow for the respective cockpit. Oxygen concentration with the lever in NORMAL position will range from 25% to 70% for altitudes from sea level to 15,000 feet MSL, and from 45% to 95% for altitudes from 15,000 feet MSL to 31,000 feet MSL. When the concentration lever is set to MAX, OBOGS supplies the highest possible oxygen concentration (95%). The maximum concentration light illuminates when the lever is in “MAX” position. The BIT button activates the initiated OBOGS BIT (I-BIT) any time after engine start and the three minute warm-up. The I-BIT provides verification that the OBOGS sensor and “OBOGS FAIL” annunciator are operating properly.

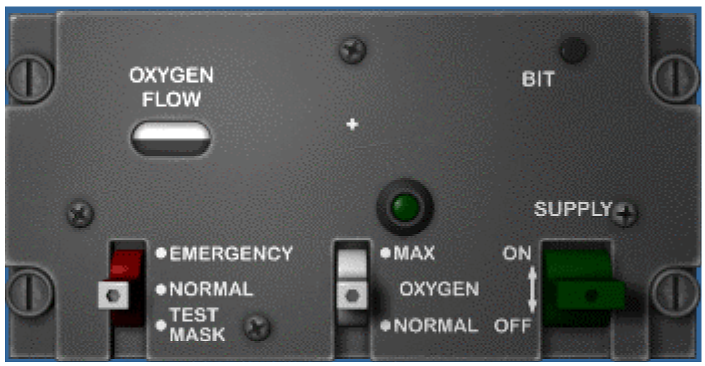

Figure 5.2.5-3. T-6 Oxygen Regulator

(4) CRU-93/A and CRU-98/A Oxygen Regulators. The CRU-93/A regulator is used in F-16 LOX-equipped aircraft (Fig. 5.2.5-3), and the CRU-98/A regulator is used in F-15 MSOGS and F-16 OBOGS-equipped aircraft (Fig. 5.2.5-4). These regulators provide automatic pressure breathing as a function of both altitude (PBA) and for G (PBG). At acceleration loads above 4 G, the regulator delivers additional pressures to the mask, a mask tensioning bladder in the rear of the helmet, and the counter-pressure vest (if worn). With each G, an addition 12 mmHg mask pressure is added to improve G-protection, to a maximum of 60 mmHg pressure at 9G. The system receives a pressure input signal from a remotely located g-valve to provide the PBG.

Figure 5.2.5-3. CRU-93/A Regulator

Figure 5.2.5-4. CRU-98/A Regulator

(5) The F-22 uses an integrated Breathing Regulator and Anti-G (BRAG) Valve that controls flow and pressure to the mask and pressure garments. The BRAG valve combines the functions of both breathing regulator and anti-G valve in one package. The BRAG valve receives inlet breathing air from the OBOGS product gas and conditioned Environment Control System (ECS) air for the anti-G air to the G-garment. The regulator portion of the BRAG valve (Figure 5.2.5-5) is mechanical, delivering non-diluted OBOGS air on demand. The valve regulates the supply and pressure of the breathing gas to the pilot for both acceleration and altitude. For acceleration pressurization, the BRAG valve requires G-suit inflation before breathing pressurization occurs to prevent loss of consciousness. During G maneuvers, the BRAG valve limits mask pressure to 60 mmHg. PBA is automatically provided by sensing cabin altitude through an internal aneroid port. For altitude, pressure breathing is initiated at about 39,000 ft and readies a maximum of 70 mmHg at 53,000 ft.

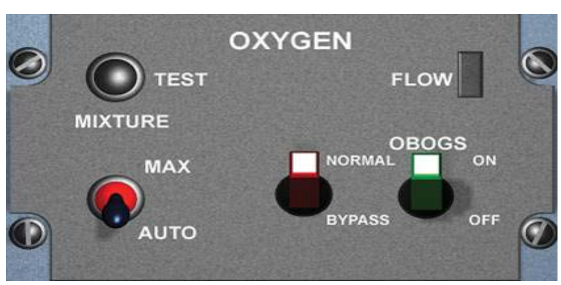

Figure 5.2.5-5. F-22 BRAG Valve Panel

The following controls and indicators are located on the front panel of the regulator:

OBOGS – This controls OBOGS operation. Positioning the switch to ON provides electrical power to the OBOGS and opens the OBOGS inlet valves allowing ECS air to operate the OBOGS.

Air Supply – The air supply switch has two positions: NORMAL and BYPASS. Positioning the switch to NORMAL allows OBOGS breathing air to be supplied from the BRAG valve to the oxygen mask with a constant safety pressure. Positioning the switch to BYPASS supplies ECS conditioned (pressure, temperature, and humidity), C/B filtered (if C/B filter is installed), regulated air (21 percent oxygen concentration) at a slightly higher safety pressure. The OBOGS and air supply switches are interlocked to prevent ON and BYPASS from being selected at the same time.

Mixture Switch – The MIXTURE switch allows control of the OBOGS oxygen concentration. With the switch in AUTO, oxygen mixture is automatically controlled as a function of cockpit pressure. With the switch in MAX, the OBOGS produces the maximum oxygen concentration.

Test Button – The TEST button activates pressure breathing and inflates the counter-pressure vest and G-suit. The amount of pressure is dependent upon how far the button is depressed. The maximum pressure is equivalent to pressure breathing at 9.0 G.

Flow indicator – standard, white indicates flow, black indicates no flow.

5.2.6. Oxygen Masks and Connectors

5.2.6.1 Quick Donning Oxygen Masks. Quick donning oxygen masks are designed for quick donning with one hand. In the event of a loss of cabin pressure or exposure to smoke and fumes, aircrew members must have access to 100% oxygen immediately.

(1) MBU-10/P. The MBU-10/P Quick Donning Oxygen Mask is designed to deliver oxygen from a regulator and provide protection from smoke, carbon monoxide, and other incapacitating gasses. These masks are used aboard C-130, E-6A, and P-3C aircraft. The MBU-10/P consists of a suspension assembly and an oxygen mask assembly. The hanging suspension holder is mounted in the aircraft to facilitate stowage.

(2) 358-1506V quick-don mask. The 358-1506V is designed for quick donning with one hand (Fig. 5.2.6-1). The vented anti-smoke goggles are worn with the quick-don assembly. It features one universal-size mask molded from silicone. The mask incorporates a manually operated vent valve to purge the goggles. The assembly provides adequate protection to 43,000 ft when used with a compatible pressure-demand regulator. The mask suspension assembly provides automatic switching from the headset microphone to the

mask-mounted microphone when unfolded. The 359 series quick-don mask (Figure 5.2.6-2) is a variant of the 358, featuring a mask-mounted regulator.

Figure 5.2.6-1. 358 Series Quick-Don

Figure 5.2.6-2. 359 Series Quick-Don

5.2.6.2 Pressure-Demand Oxygen Masks. Pressure-demand oxygen masks are qualified to hold positive pressure delivered from the regulator. The mask forms a seal around the face to get the maximum benefit from the regulator.

(1) MBU-5/P Mask. The MBU-5/P mask is a two-piece mask (hard shell and facepiece) that provides even distribution of sealing force around the mouth and nose (Fig. 5.2.6-2). It is available in four sizes: short narrow, regular narrow, regular wide, and long narrow. It incorporates a combination inhalation/exhalation valve, which requires 1 mmHg greater pressure than mask cavity pressure to exhale.

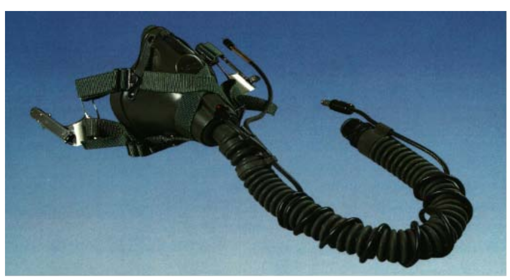

Figure 5.2.6-2. MBU-5/P

(2) MBU-12/P Mask. The MBU-12/P mask is designed to be worn over the face forming a seal on the cheeks, over the bridge of the nose, and under the chin (Fig. 5.2.6-3). The mask provides facial protection from projectiles and fire, is qualified for depths up to 16 ft under water, and permits utilization of the Valsalva maneuver to equalize pressure in the middle ear during descent. The basic MBU-12/P subassembly is a lightweight, low-profile oxygen mask. The mask features an integrated face form and hard shell. The mask has a combination inhalation-exhalation valve and a flexible silicone hose. The hose length may be adjusted via the anti-stretch cord inside the hose. The typical mask assembly contains offset bayonets for attaching the mask to the

helmet, a three-pin bayonet connector to attach the mask to an oxygen connector, the appropriate cables to connect the mask to the aircraft intercommunications system, and a microphone.

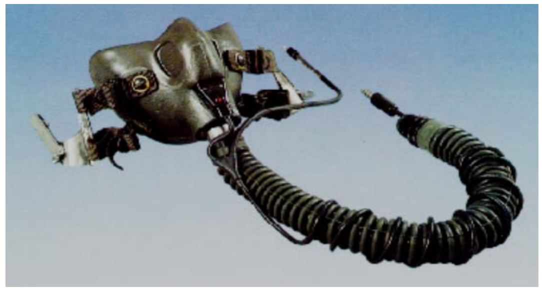

Figure 5.2.6-3. MBU-12/P

(3) MBU-20/P Mask. The MBU-20/P mask was designed for use in PBG- and PBA- equipped high-performance fighter/attack aircraft (Fig. 5.2.6-4). However, it is also used as a replacement for the MBU-12/P in non-PBG/PBA applications. The MBU-20/P oxygen mask is available in five sizes. The MBU-20/P was developed for PBG/PBA breathing schedules up to 60,000 ft and features an oxygen supply hose designed to reduce flow resistance. The lightweight, low-profile mask contour provides optimal mask/face sealing capabilities while minimizing visibility restrictions. It also features separate inhalation and exhalation valves that minimize breathing resistance and reduce aircrew fatigue. The oxygen supply hose incorporates a fitting for a helmet bladder supply hose (although some hoses may be ordered without this fitting). The inflating helmet bladder pulls the helmet back, therefore tightening the mask to maintain a leak proof seal. This helmet bladder supply hose and male quick-disconnect connector interfaces with the female connector attached to the helmet.

Figure 5.2.6-4. MBU-20/P

5.2.6.3 Oxygen Connectors. Oxygen connectors generally serve the purpose of connecting the aircraft oxygen supply hose from panel-mounted oxygen regulators to the breathing mask and, when required, to the chest counterpressure vest (CSU-17/P).

(1) CRU-60/P Oxygen Connector. The CRU-60/P is designed to ensure positive locking and prevent flailing during an ejection (Fig. 5.2.6-5). The CRU-60/P is normally secured to a dovetail mounting plate on the pilot's chest and attached to the parachute harness. It connects to a standard three-pin bayonet connector and incorporates an omni-directional elbow to ensure proper alignment of disconnect forces during an ejection. This fitting also has an anti-suffocation valve that induces increased breathing resistance if a disconnection at the inlet occurs.

Figure 5.2.6-5. CRU-60/P

(2) CRU-94/P Oxygen Connector. An integral component of the COMBAT EDGE system, the CRU-94/P Integrated Terminal Block (ITB) provides PBG capability to tactical aircrew and provides an additional port for a counterpressure vest (Fig. 5.2.6-6). The ITB distributes pressurized breathing gas from the aircraft-mounted regulator to the pilot's oxygen mask and counterpressure vest (when worn). When the counterpressure vest hose is not connected, the fitting is equipped to relieve pressure within the ITB and vents at 32-39 mmHg. Normal COMBAT EDGE pressure schedule reaches 60 mmHg at 9 G, so when the port is not plugged, the pilot will have less pressure than normal. This may be significant, as studies show that PBG at 60 mmHg produced higher G protection than at lower pressures (Balldin et al., 2005). When the vest is worn, the vest port connects to the vest supply hose using a four-pin connector. Like the CRU-60/P, the CRU-94/P has a standard emergency oxygen inlet port. When the counterpressure vest is not used, the CRU-60/P may be used in place of the CRU-94/P.

Figure 5.2.6-6. CRU-94/P

(3) CRU-120/P Oxygen Connector**.** This connector combines the features of the CRU-94/P with a CRU-79 regulator. It allows the COMBAT EDGE ensemble to interface with a regulated emergency oxygen system. This connector is used as part of an emergency oxygen backup system. It is currently installed on USAF OBOGS-equipped F-16s. The CRU-120/P extends emergency oxygen duration by accurately regulating oxygen delivered during emergency conditions.

5.2.7. Emergency Oxygen Cylinder Assemblies

5.2.7.1 High-Pressure Oxygen. Emergency oxygen assemblies may be found mounted on ejection seats, inside parachutes, or inside a passenger oxygen kit (POK). These assemblies are used for emergency oxygen during descent from ejection or bailout, aircraft oxygen system failure, or cabin pressure failure. When aircraft fly at or above 25,000 ft, emergency oxygen must be available for all aircrew and passengers.

Emergency oxygen cylinder assemblies provide 10 min worth of oxygen, generally enough for a free-fall from 50,000 ft to 14,000 ft. The cylinder's initial pressure is 12-14 in. wg and initial flow rate is 10-12 L/min. The flow rate decreases as pressure decreases, resulting in a flow rate of about 1 L/min during the 10th minute.

Emergency oxygen assemblies consist of a high-pressure oxygen cylinder, valve assembly, valve-to-mask tube, connector assembly, and pressure gauge. There are different configurations with slight variances, as shown in Table 5.2.7-1.

Table 5.2.7-1. Types of Emergency Oxygen Assemblies

Emergency Oxygen Cylinder	Description
The H–2 assembly	Is used in certain aircraft for passengers; the H–2 may be thigh-mounted or used in a carrying bag.
The MD–1 assembly	Is placed in all back style parachutes. The hose and connector assembly length is 28 inches total. The exposed pull cable length is 11.56 inches.
REDAR–K46–01	Is used with the Advanced Concept Ejection Seat (ACES) II seat. The major differences to other types of cylinders are hose length, housing, hose adapter, actuating mechanism, and clamps.

5.2.7.2 Low Pressure Oxygen. Portable oxygen assemblies are stored inside multiplace aircraft that have an operational ceiling above 35,000 ft. The assemblies allow aircrew members to move about the aircraft to perform duties and may also be used for in-flight emergencies. These assemblies utilize type A-21 regulators with no dilution. The duration of the oxygen flow is variable, lasting 4 to 30 min, depending mostly on activity level.

5.2.7.3 Emergency Passenger Oxygen System (EPOS) (Fig. 5.2.7-1*).* The EPOS is a vacuum-sealed, self-contained protective breathing device typically used by aircrew members and/or passengers during emergencies. It provides oxygen during aircraft decompression and when smoke and fumes are present. The system consists of five major components: hood, oxygen cylinder, carbon dioxide controller, neck seal, and storage pouch. The duration of oxygen flow depends upon the user's body weight and activity level.

Figure 5.2.7-1. Emergency Passenger Oxygen System (EPOS)

5.2.7.4 Protective Breathing Equipment (PBE) (Fig. 5.2.7-2). PBE consists of a lightweight emergency escape breathing device or protective breathing equipment that is designed to provide respiratory and eye protection to the user. The system consists of four major components: a solid state oxygen supply source; a chemical scrubber for carbon dioxide and water vapor; a loose-fitting hood with a head harness and neck seal to enclose the head and provide the breathing environment; and a venturi "pumping" arrangement powered by the oxygen generator, which recirculates the breathing gas within the hood. The rated duration of this device is 15 min. It should be periodically inspected every 30 days. To determine serviceable condition, check the window on the side of the storage case for a blue or pink color. Blue indicates a serviceable condition; pink indicates an unserviceable condition, and the equipment should be removed from the aircraft and replaced.

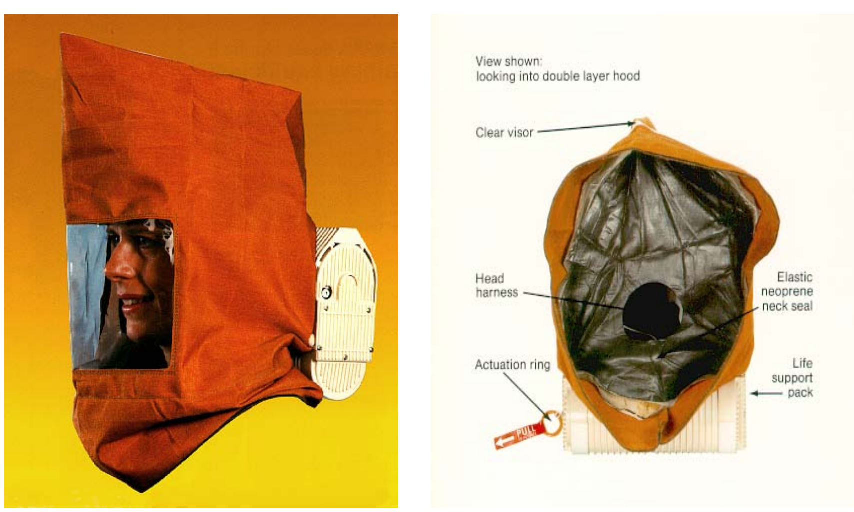

Figure 5.2.7-2. Protective Breathing Equipment

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Concepts

- Oxygen systems
- Pressure demand regulator
- Continuous flow regulators
- Diluter demand
- High-pressure oxygen
- Low-pressure oxygen
- Pressure demand regulators

Vocabulary

- Pressure breathing for altitude (PBA)
- Pressure breathing for G (PBG)
- Gaseous oxygen
- Oxygen gas - low pressure
- Oxygen gas - high pressure
- Liquid oxygen
- Onboard oxygen generating system (OBOGS)
- Molecular sieve oxygen generating systems (MSOGS)
- Combined advanced technology enhanced G ensemble (COMBAT EDGE)
- Regulated emergency oxygen system (REOS)

6. PERSONAL EQUIPMENT EFFECTS

Success of the human weapons system in the hostile environment of flight requires unique equipment and training. The physiological capacity of aircrew is amplified through the use of technology designed into aircrew flight equipment. T.O. 14-1-1 USAF Aircrew Life Support Equipment and Ensemble Configurations provides listings of all USAF aircraft and the personal equipment qualified for use in each. USAF aircrew personal equipment is designed to provide protection and enhance performance of crewmembers performing USAF missions in various aircraft. Benefits achieved by use of this equipment typically come at a price. Just as wearing a coat in winter to be more comfortable restricts movement, the design and function of aircrew personal equipment may cause some discomfort or restriction in movement. However, wearing an oxygen mask, anti-G suit, night vision goggles, or other aircrew personal equipment provides the ability to function effectively in environments where performance would be significantly or completely negated without such equipment.

6.1. NVD, HMD, & JHMCS

6.1.1. Night Vision Devices (NVDs)

Lt Eric G. Chase, Capt Mark White and Maj Steve Dawson

6.1.1.1 Introduction. The battlefields of prior generations saw action most often during periods of daylight when visual acuity was best. Indeed, vision was a limiting factor concerning the most effective time to launch an assault. Only the most important covert missions would be carried out at night, when the element of surprise was best facilitated by darkness and suboptimal enemy performance could be anticipated in response. However, while enemy performance was degraded as a result of poor vision, the offensive force could expect a comparable reduction in its own performance due to this same limitation. Today, technology has advanced to such a degree that human visual limitations have been significantly mitigated. Nighttime battlefield operations are now carried out regularly and with much greater success.

Night vision devices (NVDs) have been instrumental in overcoming the human limitations to nighttime operations. NVDs encompass all technologies used to enhance night vision, and they have been used for decades, dating back to World War II. These older generation devices used an infrared (IR) illuminator, which emitted a beam of IR light. This IR light, invisible to the unaided human eye, would reflect off objects in the viewing scene and bounce back to the device. The emitted IR beam can be thought of as a flashlight; albeit a flashlight the naked human eye cannot detect. The device was sensitive to the reflected IR light, and it would “reconstruct” the scene using wavelengths of light the human eye could perceive. This technology was revolutionary but produced a poor image that was often distorted. The devices had many limitations, including a short life span. In addition, enemy nations quickly found ways to use their own night vision devices to observe the IR beam emitted from these NVDs. Now the technology effectively made the user a target. As such, this technology quickly became obsolete. Almost immediately, work began on developing a *passive* technique, one which increased nighttime visual acuity using only available light. The image intensifier (called I^2 technology) filled this need.

Still in use today, I^2 technology continues to represent the crux of night vision goggle (NVG) function. Unlike the older technology detailed above, image intensifiers are completely passive in operation and are based on the principle of light amplification. The devices greatly amplify the ambient light produced by the moon and stars for the human eye to more easily see a poorly illuminated scene. These devices do not require a projected IR light, thereby taking away the enemy's ability to observe IR illuminators. Because they amplify ambient light, it is of paramount importance to note that image intensifiers (and, thus, NVGs) cannot function in *complete* darkness. There must be some minimum level of light for the image intensifier to amplify. Amplification of this light is what enhances scene detail and subsequent visual acuity. While NVGs intensify ambient light levels within the visible spectrum (400-700 nm), it is important to note that they also amplify light in the near infrared range. Thus, unfiltered NVGs intensify light in the range of 570-930 nm.

6.1.1.2 Image Intensification. Stating that "NVGs amplify light" is a phrase subject to subtle but important semantics. Strictly speaking from the standpoint of physics, photons (and, therefore, light) cannot be amplified. As such, light must be converted to a signal that *can* be amplified (Fig. 6.1.1-1). Electrons, which are readily amplified, are the perfect intermediaries. In the simplest of terms, ambient photons entering the image intensifiers of NVGs are converted to electrons. These electrons are then amplified in number up to 1,000-fold. After this amplification step, the resulting electrons are converted back to photons once again, such that the NVG user now perceives an enhanced scene with much greater illumination and visual acuity.

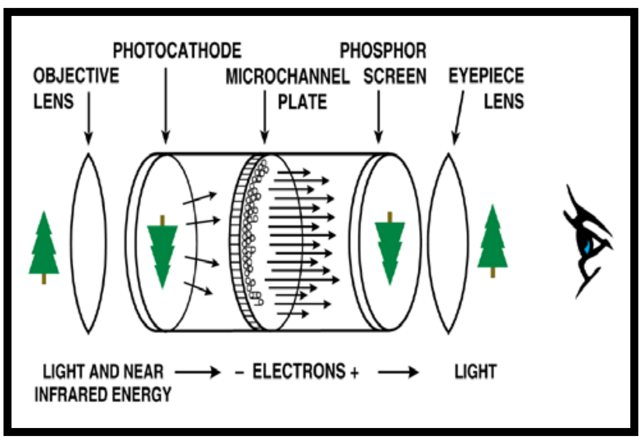

Figure 6.1.1-1. Image Intensification

The complete story of the evolution of image intensification and the physics by which it is governed is astonishingly complex. However, a fundamental description of all the components and their contributions to the enhanced NVG image is possible with a basic understanding of chemistry and physics. This figure represents an exploded view of the image intensifier tube and its components.

The image intensifier tube, with a diameter less than that of a quarter, is housed within the NVG and consists of three core components: the photocathode, microchannel plate, and phosphor screen. For our purposes, the photocathode can be thought of as little more than a glass disk coated on one side with a substance called gallium arsenide (GaAs). GaAs coats the side of the photocathode adjacent to the microchannel plate.

When photons enter the objective lens of the NVG, they first encounter the photocathode. This light interacts with the GaAs coating on the opposite end of the photocathode. Inherent properties of the GaAs are such that incident photons cause oxidation, e.g., an electron is liberated from the GaAs (these liberated electrons are depicted as arrows in the above diagram). This step represents the conversion of a light signal to an electrical signal.

As shown in Figure 6.1.1-2, the electrons liberated by the GaAs at the photocathode travel to the next component of the image intensifier tube, the microchannel plate (MCP). This is arguably the most fascinating component of the entire system. The MCP is a wafer-thin disk of glass that contains 10-11 million microchannels within it. Electrons liberated at the photocathode find their way into the MCP via one of the microchannels. Once inside, electrons strike the inner walls of the microchannels. To ensure collisions along their walls, all microchannels within the MCP are oriented at an 8º angle to the horizontal. The distal end of the MCP maintains a positive charge to ensure that a current can be maintained that keeps "pushing" the negatively charged electrons downstream through the microchannels. Each time an electron strikes the inner wall of a microchannel, an additional electron is liberated from that microchannel. This results in an exponential increase in the number of electrons travelling through the MCP. The first collision an electron makes yields 2 electrons, those two yield 4, then 8, 16, and so on down the length of the microchannel. Ultimately, for every one electron that enters one of the millions of microchannels, up to 1,000 are produced. This is the amplification phase of image intensification.

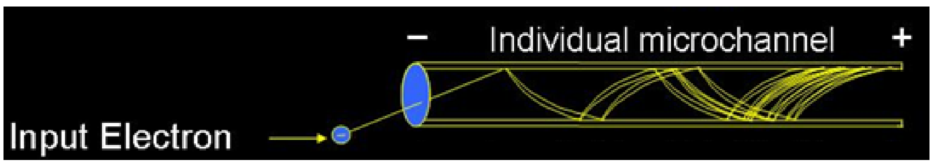

Figure 6.1.1-2. Microchannels

As the electrons exit the MCP, they next encounter the phosphor screen. This component of the image intensifier is responsible for converting the electrical signal back to a light signal. The amplified electrons strike the phosphor screen, causing it to release photons with a characteristic green color. The light emerging from the phosphor screen is exactly proportional to the number and location of the electrons striking it at each point. An intensified image results and is viewed through the eyepiece lens.

Of note are two key features regarding the phosphor screen. First, an inherent property of optics dictates that an image be inverted when light passes through a lens (as illustrated above at the photocathode). Thus, prior to viewing the light emitted by the phosphor screen, a fiber optic "twist" reinverts the image exactly 180º. Next, it should be appreciated that the characteristic green color of NVGs is not happenstance. The human eye is most sensitive to green light, so NVG engineers ensured selection of a phosphor that emits light of that color.

6.1.1.3 Performance Factors. This commentary will not concentrate on the specifics or mechanisms of focus and adjustment. However, it must be made clear that properly focused NVGs will not result in the user developing a headache. If NVGs are not focused properly, it is not uncommon for the user's eyes to accommodate for a short period of time. Over an extended period, however, the eye muscles will become fatigued and unable to maintain focus. This results in a gradual loss of visual acuity and often causes severe eyestrain, headache, or both.

It is critically important to understand that even under the most ideal conditions, visual acuity will be degraded while using NVGs. Military specifications for currently used aviation NVGs can consistently yield visual acuities of only 20/26.5. In addition, the NVG user is essentially viewing a scene from two tiny television screens. As such, true depth perception is entirely ablated. This makes distance estimation and

subsequent closure rates particularly difficult to determine. Moreover, contrast, a vital component to scene detail, is compromised in that the viewed images will all be varying shades of green. For these reasons, aircrew must understand that a preflight assessment of the NVG image is of paramount importance.

Assessing the performance of NVGs is not unlike assessing unaided visual acuity. In fact, it requires a similar approach. During an eye exam, the Snellen chart provides the examiner with an objective means by which to measure visual acuity. The size of characters a subject can see on the chart from a known distance dictates the degree of his/her visual acuity. NVG performance is assessed using a chart especially designed for NVGs using similar theory. Of important note is that this assessment cannot be accomplished while in the aircraft, so it is incumbent on the aircrew to perform the procedures prior to flight.

Unfortunately, NVGs provide an incredible amount of information even if they are not adjusted properly. This fact can lull aircrew into the false belief that it is unnecessary to adjust the goggles prior to each flight. The only means by which to determine if the settings are correctly positioned is to assess performance using a resolution chart (e.g., eye lane or Hoffman box/ANV-20/20). Figure 6.1.1-3 represents data from a study that underscores the importance of employing a means by which visual acuity can be assessed.

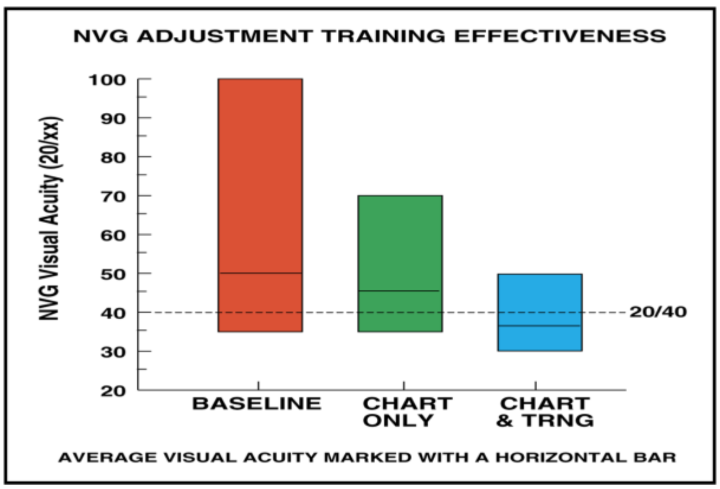

Figure 6.1.1-3. NVG Adjustment Training

Visual acuity is depicted on the Y-axis. Bear in mind, the better visual acuity, the shorter the column will be. Three different conditions were examined. First, a group of experienced NVG users were asked to adjust their goggles via whatever methods they normally used (baseline). This group of users had received no prior training, nor were they assisted with NVG focusing procedures. The NVGs were then assessed for visual acuity performance by having the subjects read from a resolution chart specifically designed for NVG use. As shown, without training or any kind of chart by which to measure visual acuity, aircrew were routinely “focusing” their goggles to acuities ranging from 20/35 to 20/100, with the average visual acuity being 20/50. Next, the subjects were given a resolution chart (but still no training) to aid them in their focusing procedures (chart only). Visual acuity improved significantly, with a range from 20/35 to 20/70, and an average of 20/45. Lastly, the group was given the resolution chart along with instruction on the proper use of the same (i.e., chart and training). Visual acuity

continued to improve, with a much smaller range of 20/30 to 20/50, and an average of 20/35.

The study above illustrates that aircrew can routinely focus their NVGs to suboptimal settings and go on to fly sorties with a dramatically decreased visual acuity. Training significantly enhances the visual acuity aircrew can expect. Additionally, these data show that training ensures all aircrew approach the same performance capability, which can be very important when different aircrew gather information in the same environment (e.g., observers estimate distance to trees). The importance to mission effectiveness and safety should be obvious.

Figure 6.1.1-4 was developed to make a point relative to NVG experience levels. It was constructed utilizing the same data as those in Figure 6.1.1-3 above, but the data here were separated into the different sites where they were collected.

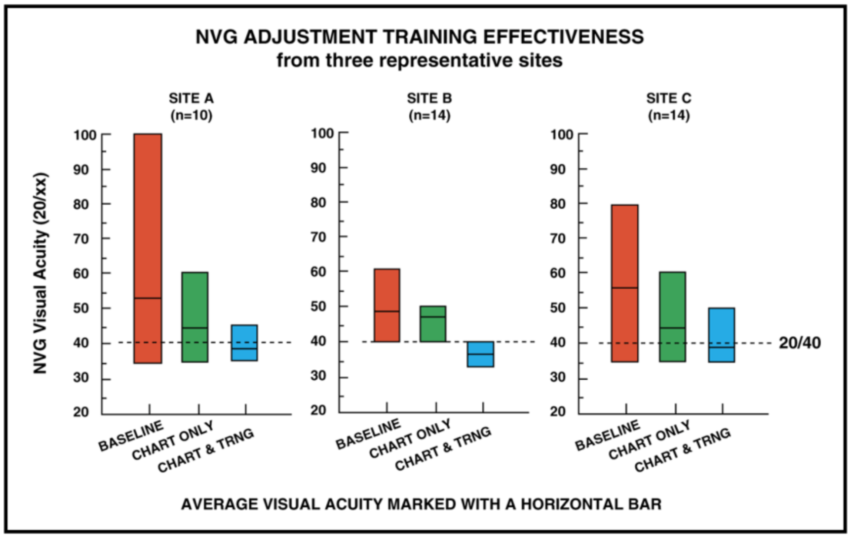

Figure 6.1.1-4. NVG Adjustment Training at Three Sites

At first glance, it would appear that aircrew at Site B were the most experienced since they had the best baseline visual acuity findings when compared to the other two sites. However, the aircrew at Site A were actually the most experienced NVG users. It appears that the most experienced aircrew are more tolerant of poor vision. The crucial point demonstrated by these data is that aircrew must guard against complacency as NVG experience builds. Further, as instructors, we must ensure that we train aircrew regarding correct focusing and adjusting of NVGs.

6.1.1.4 Field of View. Another component of training for NVGs requires the recognition of field of view (i.e., FOV) limitation. With the normal, unaided binocular vision, a standard FOV is approximately 120° vertically and 200° horizontally. The aircrew outfitted with NVGs might expect to have an FOV of 30° to 40°, depending upon the NVG in use. Eye relief and eye positioning also change FOV when using NVGs. Eye relief is defined as the distance from the back surface of the NVG ocular lens to the front surface of the eye; if the distance is greater than 20 mm, then the FOV decreases significantly. Factors affecting eye relief and ultimately FOV performance are user-head anthropometrics, use of additional life support equipment, protective gear, and the wearing of corrective lenses. Cognitively, a decrease in FOV may negatively affect human performance through an increase in task management because of the constant scanning required by aircrew to perform for them to create a complete FOV of the

surrounding environment. Simply enlarging the FOV on NVGs is not feasible because as FOV increases the resolution of the image decreases; thus, the aviator's role in the task-dependent duties of flight are not yet fully without limitations (Miller & Tredici, 1992).

6.1.1.5 Depth Perception. Even assuming focus and adjustment procedures have been carried out flawlessly and under the most ideal conditions, depth perception presents one of the most significant challenges to aircrew flying on NVGs. The ability to perceive depth via NVGs is severely degraded. In fact, one could say that this ability is effectively absent. True depth perception involves the visual acquisition of an object in three-dimensional space (rather than the "TV screens" of NVGs). Each unaided eye has a somewhat dissimilar retinal image of an object as a result of a slightly different angle of view from each eye. The retinal images fuse, allowing the brain to compute something of a triangulation, thereby providing depth perception at distances up to approximately 600 ft.

The above process is termed binocular vision, as it requires the use of both eyes, and binocular cues refer to the mechanisms by which aircrew assess depth and distance. Binocular cues are assessed subconsciously and allow for very precise distance estimation, but only at relatively short distances. While this binocular ability is lacking for NVG users, it is still possible to estimate depth using monocular cues.

Monocular cues are fundamentally different from binocular cues. While not the "true" depth perception that binocular vision provides, monocular depth perception is learned. Over time, we become familiar with the sizes and shapes of objects in our environment. We are then able to take these learned lessons and apply them to our activities. For example, there are plenty of people who live with very poor depth perception, but the cues they learn throughout life allow them to successfully drive vehicles. Among other things, they have learned that when driving along a road, nearer objects appear to be moving faster than distant objects. The same such information is used to help us determine how far away objects are when they are beyond the useful range of binocular depth perception. More pertinent to the nighttime environment, these cues are drawn upon regularly for the NVG user. Nevertheless, it is important that the NVG user understands that although monocular depth and distance information is still available and usable, it is never as good with NVGs as with unaided vision during daytime.

It is a simple fact that reduced visual acuity, field of view, and depth perception while using NVGs can easily result in illusions and misperceptions that could induce spatial disorientation. Thorough training is a crucial means by which to negate these human factor challenges inherent to NVGs. As detailed above, proper focus and adjustment training is essential to mitigate the degraded visual acuity intrinsic to NVG use. Preparing for the lack of good depth perception and field of view cues can be accomplished via training and proper planning. Only through such training can aircrew safely obtain information that may keep them from overestimating their visual acuity, field of view, and depth perception capabilities.

6.1.1.6 Human Factors: Operational Issues. In the NVG Academic Instructor Course offered at Randolph Air Force Base, we often say that NVG training courses should not teach students what NVGs can see. What NVGs see is obvious and warrants no prolonged discussion. Rather, courses should center on what the NVGs

cannot see or do. These aspects must be learned, as many are counterintuitive. Without such training, it is easy to fall victim to a variety of human factors traps.

6.1.1.7 Fatigue. As noted in the 1992 U.S. Air Force published report, *Night Vision Manual for the Flight Surgeon* (Miller & Tredici, 1992), fatigue is one of the most serious aeromedical concerns to aircrew in the operational environment. Fatigue caused by sleep disruption due to combat operations can be the most common disruptor. Activities that predispose aircrew to fatigue consist of consistent work shift changes, cumulative sleep loss, and circadian rhythm interruption. As a compounding variable, fatigue increases spatial disorientation logarithmically. Refer to the Human Performance, Fatigue, and Fatigue Countermeasures sections of this handbook for further details concerning fatigue, sleep, and circadian rhythms.

NVGs are a compounding variable to fatigue when considering the risk assessment of night operations with the possibilities of disrupted circadian rhythms, work shift reversals, and cumulative sleep debt. NVGs provide operators with a false sense of security by enabling them to function in an environment that would not be possible without the use of NVGs. Unless preventive measures are taken to identify symptoms of fatigue, such as easy distractibility, inattention to detail, slowed reaction time, poor judgment, irritability, and coordination problems, aircrew members might assume they are capable of peak performance at the least opportunistic time, thus creating a situation for a mishap. Fatigue induced by sleep disruption can be counteracted by a simple and strictly enforced sleep policy; refer to the Human Performance, Fatigue, and Fatigue Countermeasures section of this handbook for further details concerning sleep countermeasures (Miller & Tredici, 1992).

Additional types of fatigue an aircrew might incur with the use of NVGs are physical, psychological, and visual fatigue. The physical aspect is in reference to the additional weight of the NVGs (≈ 0.7 kg) to the neck, while psychological fatigue refers to the arduous, task-dependent aspects of operations at night and the associated stresses, all of which can be prevented through exercise (e.g., specific isometric neck strengthening exercises) and acquisition of job-duty knowledge, skills, and abilitie, respectively. Visual fatigue, also known as asthenopia, can be reduced by wearing of properly prescribed eyeglasses, training, thorough NVG maintenance habits of adjustment, and controlling interfering light sources (Miller & Tredici, 1992).

6.1.1.8 Life Support Integration. The integration of NVGs to the operational aspect of aircrew life support equipment is another factor that may give rise to problems. Aircrew may incur problems with their chemical defense gear, helmet-mounted devices, crash and ejection procedures, and any additional eyewear. Problems might include, but are not limited to, reduction in field of view, increased risk of neck injury due to helmet weight, increased risk of injury due to the additional helmet weight and its effect on crash tolerance under G-forces, and diminished eye protection because of improper compatibility with dust/wind goggles. The life support issues of concern are preventable through proper education of aircrew on all individual equipment and their functional integration into the operational environment (Miller & Tredici, 1992).

6.1.1.9 Cockpit Compatibility. The incompatibility of NVGs to the operational environment of the cockpit was a potentially debilitating issue. Any small amount of light that gleams from within or into the cockpit can render NVG technology dysfunctional, i.e., too bright. One resolution to the issue of cockpit lighting was to

develop a blue-green filter for NVGs and design cockpit lighting based upon the blue-green light spectra. The benefits are three-fold: first, the short wavelength of the blue-green lights will make it easier for the aircrew to see instrumentation; second, the Purkinje shift is less marked due to the ease of sight for the blue-green light when compared to a red light; and third, blue-green lights are less detectable by the enemy using NVGs. Military specification lighting is available when considering the use of NVG and is required under specific circumstances, for internal and external cockpit lighting applications, when in operational use (Miller & Tredici, 1992).

6.1.1.10 Environment Compatibility. As stated earlier, modern NVG intensifier tubes are capable of harvesting light in the near IR wavelengths. Trees are very readily seen when viewed at night under NVGs. The chlorophyll present in leaves emits light very strongly in the near IR region, exactly where NVGs are sensitive. During certain times of the year, aircrew may become accustomed to seeing a given field of trees clearly as a result of the chlorophyll-containing leaves. However, trees without leaves (and therefore without chlorophyll) can be very difficult to see. In fact, at times when trees have shed their leaves, the entire tree can seem to have disappeared. The normal human reaction to such a situation would be to get closer such that more of the scene can be resolved. As a rule of thumb, whenever aircrew attempt to make something appear at night the way it appears during the day, they are too close! Entire fields of leafless trees provide a particularly dangerous setting for low-flying aircrew. Situations can arise in which a low-flying aircraft collides with a single leafless tree that was just a bit taller than all of its neighbors. In fact, this is such a well-known and dangerous trap that these tall, hard-to-see leafless trees have been given names in the NVG community. They are very commonly called snags or, more foreboding, widow-makers.

One of the most dangerous situations that can be experienced during NVG operations is flight into undetected meteorological conditions. Generally, aircrew flying fixed wing aircraft will not be susceptible to inadvertent weather entry due to the flight altitude at which most missions are flown and the distances at which weather systems are avoided. However, certain missions (e.g., low levels) and flight conditions in certain areas (e.g., fog formation in coastal and mountainous areas) may make fixed wing aircrew more susceptible to this hazard. As discussed above, NVGs can harvest portions of the near infrared energy spectrum. These wavelengths tend to pass through light moisture more easily than visible wavelengths. As a result, what may be a visible area of light fog or rain during daytime may be virtually invisible to aircrew viewing the same scene at night with NVGs. Added to the dilemma is the fact that the thinner areas of moisture may mask areas that have significant moisture content. This can result in a gradual loss of scene detail as the weather system is penetrated, ending in a situation where there is virtually no visual information.

Perhaps even less intuitive than the above scenario is the potential danger posed by new obstruction lighting. In 2008, a Flight Safety Flash was issued by the Canadian Air Force's Directorate of Flight Safety that identified some red obstruction lighting systems that were clearly visible to the naked eye but not visible to NVGs. Surely, the idea that the naked eye can see something that NVGs cannot is a profoundly counterintuitive notion. Therein lies the human factors trap: it is frighteningly easy to become overreliant on the visual information NVGs provide (or, in this case, do *not* provide), even when that information is grossly incorrect.

New obstruction lighting systems employ light-emitting diodes (LEDs) instead of traditional incandescent sources. Aviation Red light ranges from about 610 to 700 nm, and military grade aviation NVGs with the corresponding filter sets are mostly sensitive to energy ranging from 665 to 930 nm. Because LEDs have a relatively narrow emission band and do not emit infrared energy like incandescent lights, it is possible for them to meet FAA requirements for Aviation Red but be below the range in which aviation NVGs are most sensitive.

On 6 March 2009, the FAA published a Safety Alert for Operators (SAFO) addressing this issue (FAA, 2009). They recommended action that precisely parallels the NVG Academic Instructor Course philosophy of training in terms of educating flyers regarding what NVGs cannot do:

> "Pilots, directors of operations, chief pilots, training program managers, and training centers either using or providing training for NVGs should advise pilots of the limitations outlined in this SAFO and ensure such information is incorporated into the pilot NVG training program."

As aerospace and operational physiologists, it is our duty to understand NVG limitations and pass them on to our students to enhance mission effectiveness and safety. Again, what the NVGs *can* do is patently obvious, but the NVG limitations detailed in this commentary must be *taught*.

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Technical Order 14-1-1 USAF Aircrew Life Support Equipment and Ensemble Configurations

Recommended Readings

AETC NVG Course Instructor Guide

Vocabulary

Night vision devices (NVDs)

6.1.2. Helmet-Mounted Devices (HMD)

Provision of aircraft or weapon displays on a visor or other device mounted to the helmet, helmet-mounted devices (HMDs), has become common in modern aviation; from fast jets to helicopters and in every crew position.

6.1.2.1 Background. The HMD performs one or more of the following functions: (a) displays pilotage or gunnery imagery from I^2 or forward-looking infrared radar (FLIR) sensors; (b) presents strategic, tactical, and operational data on demand, serving as an information management system; and (c) senses head/eye position and motion for the purpose of designating targets, directing sensors and weapons, and activating switches. In general, well-designed HMDs should enhance aviator situational awareness and increase mission effectiveness.

In the most basic terms, an HMD minimally consists of "an image source and collimating optics in a head mount." There are four major elements in this type of system: image source (and associated drive electronics), display optics, helmet, and head/eye tracker. The image source is a display device upon which sensor imagery is produced. These sources typically have been miniature cathode ray tubes (CRTs) or I^2 tubes. Other miniature displays rapidly are becoming alternate choices. The display optics are used to couple the display imagery to the eye. The optics generally magnify and focus the display image. The helmet, while providing the protection for which it was designed originally, serves additionally as a platform for mounting the image source and display optics. The tracking system couples the head/eye line of sight with that of the pilotage sensor(s) (when mounted off the head) and weapons. Lining up each of the elements is the epitome of human factors integration in that one must consider reduced strain to the eye and muscles supporting the device, stability of the platform (e.g., helmet) to minimize image distortion, and fidelity of symbology to match simulator experience or other aircraft displays. Thus, the overall goal of HMDs is to effectively interface the aviator/crewmember with the aircraft and associated systems, which allows the aviator to acquire and maintain situational awareness.

6.1.2.2 History. The modern HMD is not a new concept. Its invention has been attributed to Gordon Nash, a British researcher, who explored alternative methods of providing additional information to the aviator in the 1950s. One can trace the concept of using the helmet as a platform for a fire control (weapon aiming) back to 1916, when Albert Bacon Pratt developed and received patents for an integrated gun helmet, perhaps the very first helmet-mounted sight (HMS). This concept was revisited in the helmet sight system (HSS) used in the U.S. Army's AH-1 Cobra attack helicopter in the 1970s. The U.S. Navy's visual target acquisition system (VTAS), developed in the 1960s, was the first fully operational visually coupled sighting system. In Army aviation, the AN/PVS-5 NVG was the first pilotage imagery HMD (first tested in 1973), and the IHADSS was the first integrated HMD (fielded since 1985). The U.S. Air Force has been testing and fielding the joint helmet-mounted cueing system (JHMCS) since the beginning of 2000 and now includes the system in most frontline fighters.

Since the 1970s, the trend has been to rely increasingly on HMD devices or systems to provide imagery, flight information, and weapons control imagery and symbology. As technology has advanced and HMDs become more complex, the human factors and physiological challenges have also increased. The first HMD system was the AN/PVS-5 series NVG, circa 1973. It consisted of second-generation image

intensification (I^2) devices "hung" on the existing flight helmet and provided no instrument. By 1989, the AN/PVS-5 had been replaced by the AN/AVS-6 aviator's night vision imaging system (ANVIS), the first I^2 HMD designed specifically for Army aviation use (McLean, 1997). ANVIS is a passive, binocular, third-generation I^2 system and has improved sensitivity and resolution over the second-generation I^2 tubes. ANVIS is attached to the helmet (e.g., SPH-4B and HGU-56/P) using specially designed mounting brackets. The recent addition of symbology to the standard ANVIS has produced the AN/AVS-7 head-up display (HUD), a complete study of human factors integration challenges! Simply, an HMD projects head-directed sensor imagery and/or fire control symbology onto the eye, usually superimposed over a see-through view of the outside world. As such, HMDs offer the potential for enhanced situational awareness and effectiveness.

6.1.2.3 Potential Problems. Their design and implementation, however, are not without problems and limitations. Virtually every HMD, concept or fielded system, suffers from one or more deficiencies, such as high head-supported weight, center of mass (CM) off-sets, inadequate exit pupil, limited FOV, low brightness, low contrast, limited resolution, fitting problems, and low user acceptance. Of the potential problems with HMDs, none are more troublesome than those associated with the interfacing of the system with the human user. The wide variation in head and facial anthropometry makes this a formidable task, requiring HMD designs rich in flexibility and user adjustments.

An HMD designer must develop a system that is capable of satisfying a large number of widely different and often conflicting requirements in a single system. Such design goals may include, but are not limited to, the following (McLean, 1997):

- Maximum impact protection
- Maximum acoustical protection
- Maximum speech intelligibility
- Minimum head-supported weight
- Minimum bulk
- Minimum CM offset
- Optimum head aiming/tracking accuracy
- Maximum comfort and user acceptance
- Maximum freedom of movement
- Wide FOV
- Minimum obstructions in visual field
- Full color imagery
- Maximum resolution
- High brightness and contrast
- No induced sensory illusions
- Hazard free
- Maximum crashworthiness
- 24-hr, all-weather operation
- Minimum training requirements
- Low maintenance
- Low design cost and minimum schedule

Another problem with HMDs is the configuration of data presented in such a way to maintain situational awareness (SA). Since configural displays promote information saliency, well-mapped information for comprehension of task goals, and ability to see trends in systems states, all of which represent the three levels of SA as proposed by Endsley (1995), the use of configural displays in integration tasks should, in turn, provide for SA development. The theory of SA provides a framework for what must take place for SA to be established and developed (i.e., information should be highly salient and related to operator goals), but SA theory does not provide a specific means by which this can be achieved (Jenkins, 2008).

Beyond the display configurations, the issue of neck strain and injury is another consideration when discussing HMD. Loading weight to the head in the form of an HMD may have significant effects on the musculoskeletal system of the head and neck complex. The head's center of gravity (COG) is located at the top of the clivus, a position that corresponds to a location that can be measured as 46.6% to the vertex of the head and 53.6% to the chin-neck intersect for a line drawn connecting the vertex of the head to the chin-neck intersect (Clauser, 1965). In a static load condition (neutral), the effort required of the extensor muscles is increased as the COG is shifted forward or the weight is increased in the HMD. It can be hypothesized that this increase of neck extensor muscle activity is necessary to generate an increased extensor moment to counteract the increased flexor moment of the added weight. During a flexing activity (e.g., during flight or while scanning), the horizontal distance of the center of mass of the head is increased from its axis of rotation. In doing this, the flexor torque, against which the extensor muscles of the neck must work to maintain the head in a static posture, increases. This explains the increase of neck extensor electromyography (EMG) due to a flexed head position.

One engineering practice that has been used to reduce this loading is the use of counterbalance weights on the helmet. The idea behind adding a counterbalance to a frontal load is to cancel out the increased flexor moment of the frontal load. By doing this, the amount of neck muscle force required to hold the head in a static position should decrease. What has been found through EMG analysis with counterbalance devices is, on the whole, mean muscle activity increased by a greater degree due to a counterbalanced load than a frontal load (Knight, 2004). One possible reason for the increased muscle activity could be head and neck stability. In the study, using a 10-muscle, 3-joint model of the head and neck, it was found that the head and neck were inherently unstable, especially around the neighborhood of an upright posture, and suggested that maintenance of head stability requires considerable co-contraction of antagonists. Although adding a load to the rear of the head to some extent counteracts the load at the front of the head, in terms of balancing moments, it may have an effect of increasing head instability.

Operationally, the strain on the neck while scanning (e.g., door scanner in a MH-60 helicopter) a counterbalanced head load could be particularly counterproductive due to the added load at the rear of the head; with the head flexed there is a net extensor moment generated by head load, which must be counteracted by a flexor muscle force. Current systems and materials have been designed to reduce or eliminate the need for counterbalancing weights, but the concern for head stability while wearing HMD is still an operational reality for crewmembers.

6.1.2.4 Human Factors Issues. The human factors elements linked to integrating HMD to the operator run the gamut from the control of weapons to commanding aircraft movement. Fielded HMD have long since replaced the once fictional cinematic depictions of synthetic environments for aviators. The advance of head- tracking technology, the use of natural head movements to steer machinery, is now a reality. Well-known examples include the head- steered machine gun on board an AH-64 Apache ground attack helicopter and its simulators, head-steered cameras and sensing probes in remote-control vehicles, and head-steered missile seekers on fixed-wing fighter jets and flight simulators. With some head control systems, it may be possible to enhance an electronically presented view of a target so as to show artificial cues to future target positions. For example, with head-steered, tele-control application, in addition to the video picture of a target, which may be delayed by several frames, a symbol representing the current position of the target might be presented based on instantaneous data collected by sensors (So, 2000). In any application that requires precision cueing and predictive selection, operators will have an advantage if tracked targets have well-defined front and rear parts to provide cue to the direction of target movement.

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Vocabulary

Helmet-mounted devices (HMDs)

6.1.3. Joint Helmet-Mounted Cueing System (JHMCS)

The challenge of integrating technology to the operator must account for both physiology and engineering limitations. When night vision goggles were introduced to the MH-60 (Blackhawk), the integration of a head-up display (HUD) monocle was a challenge in both the visual limitations of processing two distinct images concurrently and the engineering of the umbilical from the helmet to the aircraft-mounted processor. Several significant areas must be included in human factors engineering. Table 6.1.3-1, depicts the general considerations:

Table 6.1.3-1. General Considerations

Consideration	Human-Centered Automation
Workload	Programming time, transitioning between various levels of workload
Operational Situational Awareness	Ability to revert to manual operation, recovery from automation failures, errors in managing complex modes, inadequate cognitive map
Automation Dependencies	Overreliance on systems, maintaining basic and critical skills, built-in self-diagnostics masking personal diagnostic skills
Interface Alternatives	Optimizing person-machine interfaces, degradation of personal performance, selecting and presenting information for human consideration

Adapted from Handbook of Aviation Human Factors, Garland DJ (1999)

As traditional methods of transmitting information to the pilot are replaced by advanced technology, the methods to display and the rate of transmission must be considered. The flight deck or cockpit of the future may have a series of multifunction displays (MFDs) that spread across the main console, one presenting a three-dimensional map and a predictive optimal performance vector for the aircraft to follow, the other displaying systems information that is manipulated by the pilot with the use of pull-down menus. Fast forward to the future and examine the latest technology included in current frontline fighters, the joint helmet-mounted cueing system (JHMCS). Now the flat panel displays are supplemented with visual information related to weapon system status.

For those unfamiliar with JHMCS, it can most easily be compared to the superheroes in comic strips or cartoons who look at the enemy, radiate a bolt of lightening from their eyes, and POOF, the enemy has been destroyed. While not equating aircrew and superheroes, the capabilities associated with JHMCS are impressive (Fig. 6.1.3-1).

Figure 6.1.3-1. JHMCS

In a very high-tech way, the pilot is "plugged" into the system via a large cable to the back of the helmet. There is a magnetic transmitter unit fixed to the pilot's seat and a magnetic field probe mounted on the helmet. The two systems talk to each other to define helmet positioning. To project the image, the visor relief was increased and sits noticeably further away from the eyes compared to a regular HGU-55P helmet. The actual distance varies based on skull shape and how deeply set a person's eyes are; however, it is approximately 2 to 4 in. The image is projected only in front of the right eye as the majority of the population is right-eye dominant. The human factors associated with eye dominance are addressed in a following section.

Prior to JHMCS, pilots were required to maneuver their aircraft and/or manipulate their targeting pods, radars, or other sensors to lock and shoot a target. Much like the superheroes mentioned previously, the JHMCS allows the pilots to simply look at their target, lock, and shoot. Development on this type of system began in the mid 1990s. The JHMCS helmet is a modified HGU-55P helmet with a visor-projected HUD. The display includes select targeting information, threat warnings, and aircraft performance data, eliminating the need to look into the cockpit during visual air combat. It does not provide as much information as the HUD and can be decluttered to different levels depending on the pilot's preference.

The JHMCS helmet weighs approximately 4.2 lb compared to the standard HGU-55P weight of 2.3 lb. Based on pilot testimony, the additional weight is hardly noticeable after a few flights with the helmet. Pilots did indicate that following a defensive basic fighter maneuver (BFM) sortie, they noticed their neck was stiffer than normal but nothing serious enough to preclude them from using the helmet. All of this new technology comes at a price, however. While a regular helmet costs around $800, a JHMCS unit will run Uncle Sam around $100,000.

Currently, JHMCS are being delivered to F-15C/D, F-16 Block 40/50, and the Navy's F/A-18C/D/E/F units. The F-15E is scheduled for JHMCS upgrades by 2009. There is currently no plan to utilize JHMCS with the F-22A, given the already outstanding situational awareness provided by the sensors on board the Raptor. There are also several international air forces employing the system.

Speaking of situational awareness, it may be tempting to assume this additional display would be competing for attention against the many other "drool buckets" present in the jets. Aircrew, however, report that rather than competing, it actually enhances the

ability to use the other sensors more effectively. For instance, rather than having to slew a targeting pod all over trying to locate and identify a target (similar to looking through a soda straw to find a bug on the floor), you can simply look at the target on the ground, designate it, then look at your targeting pod and the designated area will already be there. Aircrew report that the system is easy to learn and integrates effectively with the other systems on board the aircraft.

Enhanced design systems mounted to the human operator will target improved communication, digitized information transmission, voice recognition, autonomous navigation systems, and portable computers for detecting problems and troubleshooting. While eye-watering in capacity, the systems must not overwhelm the human. Visual acquisition and tracking, auditory thresholds, and mental workload limitations are physiological functions that must be included in the design and employment of advanced technologies; the goal is to ensure the technology is intuitive to use and pilot friendly, as well as capable and reliable in all phases of operation.

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Concepts

Head-up display (HUD)
Joint helmet-mounted cueing system (JHMCS)

Vocabulary

Human factors

6.2. Anti-G Suits/Ensembles

William Albery, Ph.D.

The major objective of the anti G-suit (AGS) is to help protect against the detrimental effects of +Gz exposure, especially G-induced loss of consciousness or GLOC. As AGSs are developed, the trend is toward integrated aircrew ensembles (IAEs) that include the AGS as part of a zipped garment that doubles as a flight suit. IAEs are being developed that also provide water immersion protection; thermal considerations; and even chemical, biological, radiological, nuclear, and some explosive protection. One of the complaints from USAF pilots is that current flight suit ensembles have too many layers, which can lead to thermal problems, especially in temperate environments such as the Middle East. The IAE is currently being pursued as a replacement to the current AGS and its additional layers of garments.

6.2.1. Types and Features of Anti-G Suits (AGSs)

Extensive research has been done in designing mechanisms to support the cardiovascular system during high-performance flight. Different techniques have been used, varying from merely taping the lower part of the body and limbs to complicated pulsating pneumatic systems.

> *The basic theory of the anti-G garment is to supply external pressure to the lower part of the body. Pressure on the abdomen prevents descent of the diaphragm and maintains the heart-to-eye distance, while compression of the legs prevents pooling of blood and assists in maintaining cardiac output.*

6.2.1.1 Standard CSU-13 B/P AGS. The Air Force anti-G garment as shown in Figure 6.2.1-1 consists of five interconnected pneumatic bladders that support the calves, thighs, and abdomen. This "standard" anti-G suit, as it is called, was developed by the David M. Clark Company in close association with Drs. Wood and Baldes at the Mayo Clinic in the early 1940s. The suit is still the most common anti-G suit used in modern air forces. The system is controlled by a valve, which varies the amount of air entering the bladders. The higher the level of G encountered, the greater the pressures exerted on the body by the bladders. The standard AGS gives about 2 G increased protection above the normal relaxed threshold for +Gz acceleration. Bladders over the thighs, calves, and abdomen are inflated and pressure increases as a function of increasing G and provide effective lower torso counterpressure.

The AGS (Fig. 6.2.1-1), combined with the L-1 maneuver, is the best way of increasing $+G_Z$ tolerance of crewmembers in high-performance aircraft, offering 3 to 5 G elevation in tolerance. USAF pilots who transition into high-performance fighter aircraft have to demonstrate they can tolerate 9 Gz for 15 s on the Holloman AFB human centrifuge. Many trained centrifuge subjects and pilots can sustain 9 Gz for 1 min or more when protected with the standard AGS and performing a good straining maneuver. The uninflated AGS alone gives approximately 0.4 G protection, while the inflated AGS gives approximately 1.0 to 1.5 G protection over a 15-s duration. The human tolerance range for subjects wearing an inflated AGS and performing a good L-1 maneuver varies from 7.5 to 9.0 G.

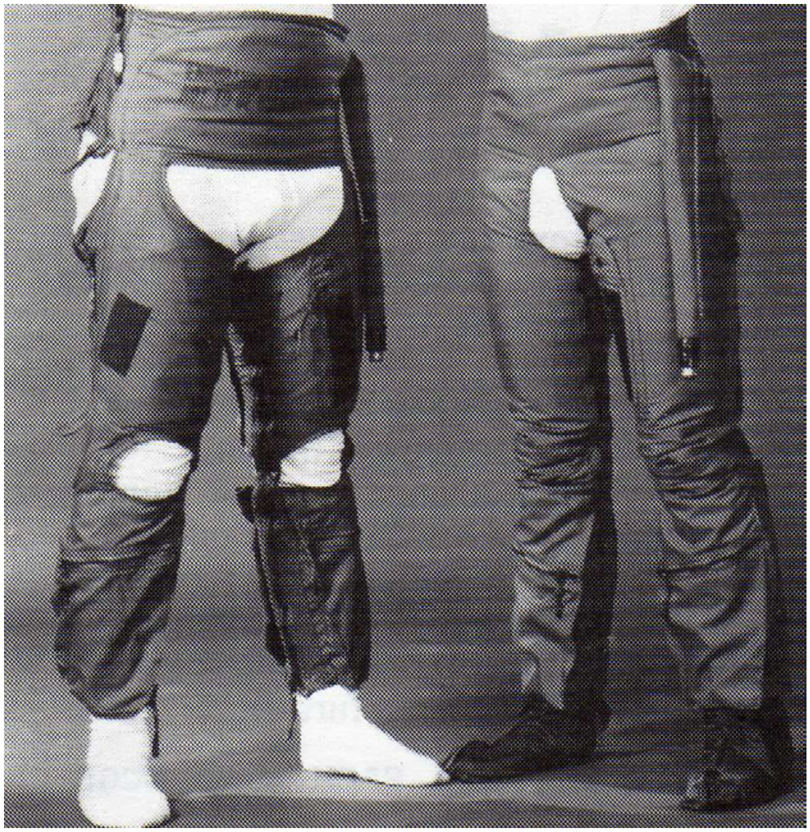

Figure 6.2.1-1. Standard AGS, CSU-13 B/P (on left, with pneumatic bladders over the thighs, calves, and abdomen); Full Coverage AGS, the ATAGS (on right, note no pressure socks)

6.2.1.2 ATAGS G Suit. The advanced technology anti-G suit (ATAGS) is considered a "full coverage" anti-G suit (Fig. 6.2.1-1). The ATAGS covers the entire legs with a continuous bladder for uniform pressurization. The "pressure socks" are no longer a part of the ensemble. The ATAGS covers 95% of the lower torso of the pilot and has been shown to provide a 60% improvement in G-time tolerance on the AFRL centrifuge (Krutz et al., 1990). The ATAGS is currently flown as the anti-G suit trousers in the F/A-22.

6.2.1.3 Integrated Aircrew Ensemble. The IAE is currently under development by the Aeronautical Systems Group (77th AESG) at Brooks City-Base in cooperation with industry. The IAE will incorporate the AGS and other personal equipment pilots currently wear once it is fielded.

6.2.2. Degrees of Protection, Protective Techniques, and Devices

Any action or device that would increase the pressures in the hydrostatic column during increased +Gz loads should increase the level of G, and time at G, that the human operator may tolerate. This concept is the underlying basis for two commonly used G-protection principles, the active straining maneuver and the AGS. There are two types of straining maneuvers in use, the M-1 and the L-1 maneuvers (Leverett & Whinnery, 1985). The M-1 (M = Mayo Clinic) consists of pulling the head down between the shoulders, slowly and forcefully exhaling through a partially closed glottis and

simultaneously tensing all skeletal muscles. The L-1 (L = Leverett) maneuver is similar to the M-1 except the exhalation is forcefully applied to a completely closed glottis. When properly executed (about every third second), the exhalation phase of these maneuvers can result in an increase of intrathoracic pressure of approximately 50 to 100 mmHg, which raises arterial pressure at eye level. Adding 1.5 Gz to 5.0 Gz of G-tolerance to the straining pilot can raise G-tolerance from approximately +5 Gz to +7-10 Gz. The M-1 and L-1 maneuvers, while quite effective, are physically taxing and can interfere with speech and other communication modalities. When the maneuvers are performed for long periods (1 to 3 min), pilots can become severely fatigued. When this happens, the maneuver obviously loses its effectiveness, which, in turn, impacts on mission performance.

The standard AGS consists of bladders inserted into a full- or partial-body coverall (Fig. 6.2.1-1). The bladders inflate during the onset of acceleration. The inflation pressures usually start around 2 G and increase as G increases to a maximum pressure at +9 Gz of approximately 570 mmHg, or 11 psi, in the bladders. The external increase in pressure afforded by the G suit reduces body deformation and blood pooling in the extremities and mechanically increases internal blood pressure. The relaxed subject wearing a G suit has an increased G-tolerance of 1-2 G (Wood, 1988; Davis et al., 2008). When combined with a straining maneuver, G-tolerance can increase up to 3 to 5 G, allowing the human to tolerate +9 Gz without losing consciousness (Burton et al., 1974).

6.2.3. COMBAT EDGE (PPB and APPB)

Another method of increasing G-tolerance is by applying positive pressure breathing (PPB) or assisted positive pressure breathing (APPB). PPB or, more appropriately, pressure breathing during G (PBG) refers to the application of pressure by a regulator to the breathing gas throughout the respiratory cycle (Prior, 1995). PBG was adapted to G protection from altitude protection. In the late 1980s, the USAF developed a system called COMBAT EDGE (combined advanced technology enhanced design G ensemble). COMBAT EDGE combines PPB with the standard AGS to provide additional G protection, or a protection edge, for pilots of high-performance aircraft. COMBAT EDGE includes a counterpressure vest to help maintain intrathoracic pressure and helmet-tensioning bladder to help tighten the oxygen mask seal on the pilot's face during PBG. Assisted PPB, or APBG, is applied as the pilot inhales or takes a breath while straining. Pressures of 45 to 70 mmHg have been shown to increase G-tolerance time by increasing intrathoracic pressures, reducing the mechanical effects of increased G on respiration and reducing the effort needed to perform straining maneuvers. APBG systems for G protection are now being implemented in U.S. Air Force F-16, F-15, F-22, and F-35 aircraft with mask pressures up to 60 mmHg at 9 G.

The pressurized breathing gas results in an elevation of intrapulmonary pressure that is transmitted to the left ventricle and intrathoracic vessels, which results in an increase in systemic arterial blood pressure (Balldin & Wranne, 1980; Prior, 1995). Increased intrathoracic pressure can impair venous return unless lower body counterpressure via an AGS is applied. Breathing against PBG tends to reduce the inspiratory reserve volume of the lungs, although total lung capacity is increased under PBG. To prevent overdistension of the lungs when PBG exceeds 30 mmHg, chest counterpressure is recommended. Until recently, USAF pilots wore the counterpressure vest for COMBAT EDGE, but because of thermal complaints and the reduced threat for high G operations, the requirement to fly with the vest has been dropped for F-16 pilots. It

is currently (2009) in use by F-22 pilots where it may be needed for high-altitude protection during a possible rapid decompression above 50 000 ft. Some pilots are able to tolerate +9 Gz without having to perform a straining maneuver while protected with a properly fitted COMBAT EDGE ensemble. Other countries including Great Britain, France, Canada, Spain, Italy, and Germany are also fielding COMBAT EDGE-like systems for their high-performance aircraft. Sweden and Finland use assisted pressure breathing during G in combination with a full coverage anti-G suit. G-tolerance experiments on the Brooks City-Base, TX, centrifuge demonstrated that subjects protected with APBG in addition to the standard AGS had superior endurance on a 5 G-9 G simulated aerial combat maneuver (SACM) than those subjects protected with the standard AGS alone (Burns & Balldin, 1988). Also, in human performance studies involving subjects in the Wright-Patterson AFB (WPAFB) dynamic environment simulator (DES) centrifuge, those subjects protected with APBG systems were able to perform a simulated flying task to peaks of 9 G nearly twice as long as those subjects protected without APBG (Albery & Chelette, 1998). APBG raises the intrathoracic pressure of the subject/pilot, thus increasing eye level blood pressure and making it less fatiguing to breathe and to perform the straining maneuver (L-1) under high G for extended maneuvers.

In high-intensity wartime scenarios, pilots may be required to fly multiple, strenuous missions during the same day. A study was undertaken to investigate if up to 80 peaks at +9 Gz and 80 peaks at +8 Gz in five simulated sorties with four engagements in each sortie within a 4-hr period were feasible (Balldin et al., 2003). Nine well-trained centrifuge subjects were exposed to the above-mentioned rapid onset simulated aerial combat maneuver G-profiles in the centrifuge using the extended coverage anti-G suit with assisted pressure breathing during G. Seven of the nine subjects could endure all five sorties, even if some had extensive visual performance loss, maximal reported effort level, heart rates up to 173 bpm, and blood oxygen saturation down to 75%. Two subjects experienced GLOCs, and four cases of almost loss of consciousness occurred. Performance deteriorated during all G-exposures as measured with a tracking task, and neck muscle contraction was impaired. The conclusion was that it is possible to train subjects to withstand a large number of G-exposures.

For future high-performance aircraft design it is important to know the upper limit of various protective equipment and techniques. In a study by Burns et al. (2001), the G-tolerance up to +12 Gz was studied in six centrifuge subjects with different anti-G suits and seat configurations. The results showed that all six subjects were able to achieve +12 Gz with various combinations of +Gz-protective equipment, seat-back angle, and various amounts of straining. The data confirmed that effortless protection to +9 Gz was available using an extended-coverage anti-G suit and assisted pressure breathing with both 13º and 30º seat-back angle and to +10.5 Gz with 55º seat-back angle. With an extended-coverage anti-G suit, assisted pressure breathing, and a moderate straining, +12 Gz was definitely achievable at 55º, even with reduced anti-G suit pressure. With additional straining, +12 Gz was also achievable at the 13º and 30º seat-back angle.

6.2.4. Thermal or Other Considerations

The standard AGS has been a popular G protection ensemble because it is relatively simple, comes in numerous sizes, and is fairly universal. Because it does not cover the entire lower torso as does some other AGS, it is relatively comfortable in temperate climates. The rubber bladders that reside over the thighs, claves, and abdomen can become hot, however, and pilots complain about "hot spots" with the standard AGS. The USAF Air Combat Command (ACC) complained about the thermal issue of the COMBAT EDGE (CE) counterpressure vest several years ago. The pilots felt the vest led to overheating, thus reducing pilot effectiveness in temperate climates. A study was conducted with pilot-subjects wearing COMBAT EDGE as well as the standard AGS (STD) (Balldin et al., 2002). The subjects were heated in a controlled temperature thermal chamber at Brooks City-Base and then exposed to multiple high-G exposures on the AFRL centrifuge. Following heat stress, no significant differences were found between CE and STD with regard to core and skin temperature or dehydration level in contrast to the anecdotal information from the pilots. Use of CE did produce a significantly higher relaxed, gradual onset G-tolerance both before and after heat stress. Despite these findings, ACC requested a study to determine if the counterpressure vest impaired the acceleration tolerance up to 9 G (Balldin et al., 2005). The study report concluded that the elimination of counterpressure vest during use of PBG did not hinder an individual's ability to reach +9 G_Z or complete a short-duration simulated aerial combat maneuver G-exposure (Balldin et al., 2005). As a result of this research, ACC decided to make wearing the COMBAT EDGE vest optional for F-16 pilots but currently not for F-22 pilots as described above in 6.2.3.

Several years ago, a German manufacturer presented a novel AGS that incorporated water channels as the activating device for the suit rather than inflated air bladders. This AGS, called the Libelle (or Dragonfly), was evaluated by ACC as well as AFRL. The concept was not theoretically sound, and the AGS was not successful in either the ACC or AFRL evaluation. The concept was that garden-hose-sized water channels that ran the full length of the suit would tend to swell under G as water would be naturally drawn down into the lower torso. As these channels swelled they became elliptical, thus tightening the fabric adjacent to the channels. This tightening conferred counterpressure, and the counterpressure conferred increased arterial pressure to the pilot/subject. The Libelle was evaluated both in-flight in the F-16 and under controlled conditions on the Brooks and WPAFB centrifuges. Although the suit had some advantages (no requirement for hook-up to the jet), it did not protect as well as COMBAT EDGE with a full coverage AGS. A preliminary comparison showed that a G suit with full coverage in combination with pressure breathing during G gave a G-intensity tolerance of +9 Gz. With the Libelle it was only 6.3 +Gz (Eiken et al., 2002). It was concluded that, under the conditions tested, the G protection afforded by the Libelle suit was not adequate for use in a 9-G aircraft.

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Concepts

Simulated aerial combat maneuver (SACM)

Vocabulary

Advanced technology anti-G suit (ATAGS)
COMBAT EDGE
G-induced loss of consciousness (GLOC)
L-1
M-1

7. MISSION-IMPOSED EFFECTS

I was anxiously waiting for my clean (no bombs, no bomb racks, no external fuel tanks) F-4D to accelerate past its transient limit of Mach 2.2 for a personal record. At sea level, the wind resistance in the relatively thick air and higher temperature would have kept us from exceeding about Mach 1.1. We were rapidly climbing through 48,000 ft after taking off from Phu Cat AB, Vietnam on this functional check flight in 1970, closing in on that record at about 1125 knots (over 1290 mph, Mach 1.96). The sky above was turning black because we were above more than 85% of earth's atmosphere. While focusing on the altimeter and Mach indicator, the engine inlet ramps closing to avoid effectively choking the engines with the now-compressed air, I felt a shudder and the jet began to wobble from side to side a bit. My quest for Mach 2.3 would have to wait. I slowly pulled the throttles back to avoid compressor stalls, started a turn home to lose altitude and airspeed and called it a day. While taking off my harness and LPU, I mentioned to my back seat pilot that I sure was glad we didn't have to eject up there. He replied "Why?" I just looked at him and said "Do you think we would have made it out alive?" At nearly 50,000 ft while wearing a summer flight suit and no jacket, leaving a nearly Mach 2 aircraft into –55^{o}C air would almost assuredly have shattered the thin visors in our helmets, impaling our eyes with plastic shards, probably ripped off our helmets, mangled both arms, and then frozen them solid with most of the rest of our battered bodies before we reached an altitude where thawing would take place. Some of the guys said I should have just pressed on for the record. I think not.

Mission-imposed noise effects and thermal stress are reviewed in sections 1.5 and 1.7.

7.1. Physiologic Effects of Acceleration

Lt Col Andrew D. Woodrow, USAF, BSC; Col Robert M. Shaffstall, (USAF-Ret); William B. Albery, Ph.D.

1990 The USAF School of Aerospace Medicine laboratory functions including the centrifuge and chamber research facilities at Brooks AFB became the Armstrong Laboratory (AFSC Historical Publication).

7.1.1. Introduction

Aeromedical concern about the effects of acceleration has a long history. Concern was first stimulated as early as World War I when pilots complained of a loss of vision and consciousness during pullouts from dives in aerial combat. Interest in this area has continued until the present, where the effects of sustained acceleration have become a major limiting factor in the operation of frontline fighters and advanced trainer aircraft. Because of the higher thrust-to-weight ratio and structural strength, aircraft like the F-16, F-15, F-18, F-22, and F-35 are able to routinely fly in the +7 to +9 Gz range for sustained periods. This chapter aims to highlight the human responses to acceleration in terms of physiology, tolerance, and protective measures against the adverse effects of acceleration.

7.1.2. Basic Principles

Speed is the linear distance covered per unit of time and can be quantified as meters per second (m/s), feet per second (ft/s), miles per hour (mph), or in aeronautical terms as nautical miles per hour (kn). Velocity is speed in a specified direction. When velocity changes due to a change in speed or direction, acceleration occurs. Acceleration is the rate of change of velocity per unit of time and can be quantified as feet per second per second (ft/s^2).

- Speed = distance/time = ft/s
- Velocity = speed in a particular direction
- <u>Acceleration</u> = speed/time = ft/s^2
- Jolt = rate of increase in acceleration = G/s

The units of acceleration are defined relative to the force of gravity on Earth. Near the surface the force of gravity exerts an acceleration of 32.2 ft/s^2. That force would cause a free-falling object to attain a velocity of over 100 mph in a vacuum within 3 s. The resistance of air results in a terminal velocity of about 120 mph for parachute jumpers at relatively low altitudes. The opening of their parachute results in a deceleration (opening shock), reducing that 120 mph to less than 15 mph in less than a second.

<u>Law of Action and Reaction</u>. Newton's third law states that for every action or force, there is an equal and opposite reaction. The reaction is the inertial force of the body, which is equal to, and opposite in direction from, the accelerative force. For example, the inertial force presses a crewmember back into the seat of an aircraft during the forward acceleration on takeoff and pushes him/her forward during deceleration on landing.

The force of deceleration during parachute opening shock is from head to foot or, in the aircraft vernacular, eyeballs down (Table 7.1.2-1 and Fig. 7.1.2.1). Instead of eyeballs moving in a direction opposite the acceleration force, you could think of where your head would tend to go under each linear motion.

Table 7.1.2-1. Forces in Response to Aircraft Acceleration

Linear Motion	Acceleration Description	Physiologic Standard	Aircraft Vernacular
Backward	Backward acceleration	+Gx	Eyeballs-Out
Forward	Forward acceleration	-Gx	Eyeballs-In
Upward	Headward acceleration	+Gz	Eyeballs-Down
Downward	Footward acceleration	-Gz	Eyeballs-Up
To the Right	Right lateral acceleration	+Gy	Eyeballs-Left
To the Left	Left lateral acceleration	-Gy	Eyeballs-Right

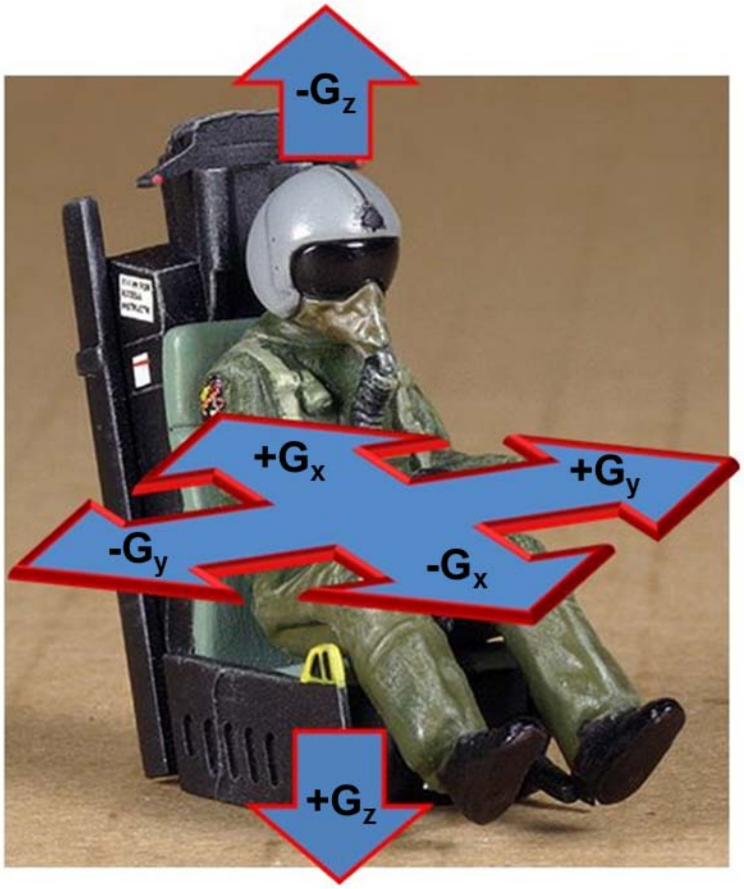

Figure 7.1.2-1. Three Dimensions of Acceleration and Vibration

- <u>+Gz acceleration (positive G)</u> occurs when inertial force acts toward the feet and the body is, therefore, forced toward the feet or aircraft seat. Examples are an abrupt recovery from a dive, turning maneuvers, or parachute opening shock. An example known to all pilots is the increase in +Gz during a level turn as shown in Figure 7.1.2-2.
- <u>-Gz acceleration (negative G)</u> occurs when the inertial force acts toward the head and the body is lifted up out of the seat. This occurs during abrupt dives or flying an outside loop.
- <u>+Gx acceleration (forward transverse G)</u> occurs when the accelerative force acts across the body at right angles to the long axis in a back-to-chest direction. The inertial force would be in a chest-to-back direction and the body would be forced back into the seat. A flyer experiences +Gx acceleration on takeoff.
- <u>-Gx acceleration (backward transverse G)</u> occurs when the accelerative force acts across the body at right angles to the long axis in a chest-to-back direction. The inertial force would occur from back-to-chest and the body would be pressed forward away from the seat. This form of acceleration occurs during arrested, or “gear up,” landings. The F-35 pilot experiences -Gx acceleration when the speed brakes are applied and tends to be thrust toward the instrument panel.
- <u>+/-Gy acceleration (right or left lateral G)</u> occurs when the accelerative force acts across the body at a right angle to the long axis in a side-to-side direction.

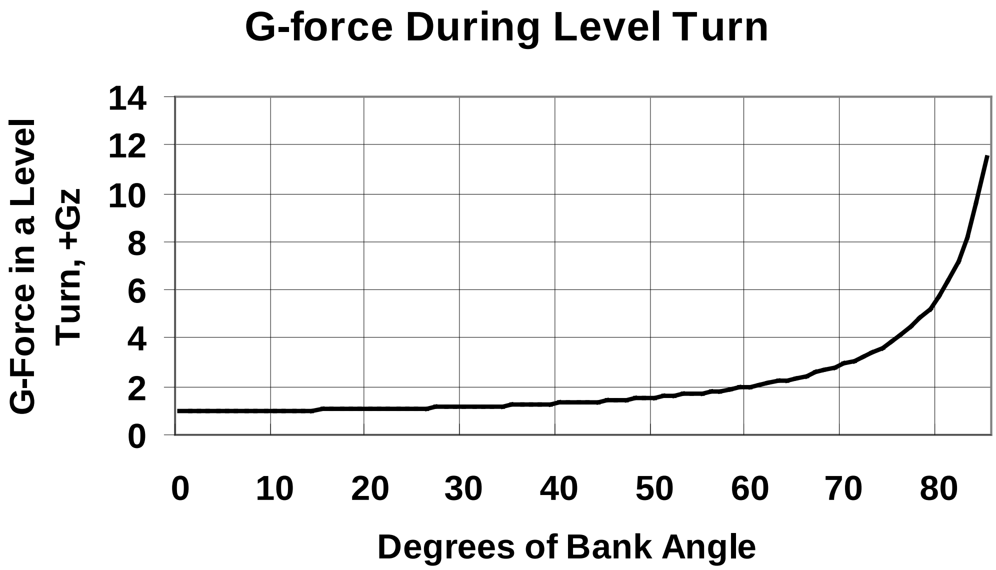

Figure 7.1.2-2. G-Force vs. Angle of Bank in a Level Turn

Based on G-force = L_A X cosine of bank angle of bank and $r=V^2/g$ X tangent of angle of bank where L_A = net acceleration perpendicular to the surface of the wing = g/cosine of angle of bank and g = G-force during a level turn

Because a 154-lb (70-kg) body weighs 616 lb (280 kg) at 4 positive G or +4 Gz, mobility is grossly restricted during acceleration. During tight turning maneuvers in a high-performance aircraft, for example, pilots are pushed down into the seat, their arms and legs feel heavy, their cheeks sag, and they become incapable of free whole body movement. Above +2 to +3 Gz, escape from a disabled aircraft would be impossible without ejection devices.

Increased gravitational fields increase the weight of body parts (von Gierke et al., 1991). Body parts can become elongated or compressed under the G vector; this can affect the shape and function of the soft internal organs including the heart, lungs, kidneys, liver, etc. Higher muscle forces are required to keep the head, torso, and limbs in desired positions. At G-forces of approximately +2 Gz, there is increased pressure on the buttocks, drooping of the face, and noticeably increased weight of all body parts; at this level of G-force it is difficult to raise oneself, and at +3-4 Gz it is nearly impossible. Experiments were conducted in the Wright-Patterson AFB (WPAFB) dynamic environment simulator (DES) centrifuge where subjects arose from a seated position and performed a whole body jump at Gz levels up to 1.8 Gz. Although most subjects had no problem standing up at 1.8 Gz, jumping and leaving one's feet was very difficult (Constable & Carpenter, 1995; Chelett et al., 1995). Above +3-4 Gz, controlled motions require greater effort, accommodation, and learning to offset loss of fine motor control. One typically cannot raise the arm at greater than 8 Gz or legs at greater than 3 Gz. Head pitching is difficult at greater than 4 Gz, and some individuals who get their heads pitched forward at high Gz (> 6 G) are unable to right themselves in the seat until the acceleration is unloaded. The hand can be raised slightly at 25 Gz. Speech is severely affected yet possible up to +9 Gz if the operator is utilizing protective techniques properly. Sensory inputs such as vision affected through eyeball deformation, vestibular orientation through the semicircular canals and otoliths, and force/weight judgments in manual dexterity tasks can be affected. Acceleration

protective equipment, as discussed in section 6.2, can either improve or limit/degrade performance through mechanical interference.

The higher the jolt or rate of increase in acceleration, from any direction, the greater the physiological effects on the body. The total force applied and the time it takes for the force to be applied must be considered when determining the effects on the body.

The greater the surface area over which a force is applied, the less the final effect on the body. Consider the consequences if an equal force is applied to a nail and to a block of wood held against the body. Since the wood distributes the force to a large area of the body, a much larger force would be required on the block of wood to produce injury. An application of this principle in flying is the shoulder and parachute harness, both designed to distribute abrupt deceleration forces over larger areas of the body.

A pilot in a high-performance aircraft may be exposed to lateral buffeting, which results in +-Gy acceleration. Spins in aircraft such as the T-6 expose the crewmembers to lateral G, but the effects are negligible.

7.1.3. Basic Physiological Effects of Acceleration

In general, the greater the magnitude of the accelerative force, the greater the effect on the body. Generally, the structural system of the body can withstand short duration forces up to approximately 25 G, with little or no permanent damage.

The body normally functions under a condition of +1Gz because of gravity. Any increase in G-force causes a proportional increase in the weight of the body. At G levels two to three times normal, it becomes impossible to move freely because of the increased body weight. Consequently, it has been necessary to install ejection seats in high-performance aircraft to enable the crewmembers to escape if necessary. Most high-performance aircraft are designed to withstand 9 G with a 50% safety factor built in before structural damage is imparted to the airframe; 9G plus 50% overload equals approximately 13.5 G maximum load. Within this range of accelerative forces, the primary physiological effect is on the cardiovascular system, since other body structures can easily withstand these forces.

The time duration a force is applied will determine the effect of acceleration on the body. These effects will vary depending on whether the body is exposed to impact acceleration or prolonged acceleration. It has been generally accepted that acceleration for a time greater than a 1-s exposure should be called prolonged acceleration, and a duration less than 1 s should be called impact acceleration. For example, jumping from a table 3 ft (0.9 m) high would produce an impact G-force of 12 to 15 positive G or +Gz for a fraction of a second with no ill effects. If a subject is exposed to 12 to 15 positive G for 2 s or longer, severe, physiological changes are produced.

The physiological effects of acceleration can be viewed from several perspectives. This section will take the systems approach. Different body systems will be reviewed, and the effects of acceleration on each system will be discussed. Prolonged acceleration affects the body in five principal ways: by restricting mobility, by impairing respiration, by affecting the cardiovascular system, by reducing visual acuity, and by stimulating the vestibular apparatus in the inner ear.

7.1.4. Cardiovascular System Effects

The hydrostatic pressures produced by +Gz passively dilate the blood vessels below the heart and result in pooling of blood within these vessels. High hydrostatic pressures cause circulating blood volume to be further decreased due to an increased flow of serum through the capillaries, causing edema formation. Both edema formation and blood pooling reduce the amount of venous blood returning to the heart, limit the heart's output, and reduce the circulating volume of blood.

If the accelerative force remains constant at blackout level for 4 to 6 s or longer, vision may spontaneously return. This occurs because of compensatory mechanisms, which increase the blood pressure to the point where blood flow to the eye resumes. The primary mechanisms in this reflex are the pressure sensitive nerve endings in the carotid sinuses and in the arch of the aorta.

When blood pressure drops in the aortic and carotid arteries, specialized receptors relay this information to the vasomotor center in the medulla. The vasomotor center responds by sending impulses to the arterioles throughout the body, causing them to constrict. This vasoconstriction increases peripheral vascular resistance and, along with an increased heart rate, causes arterial blood pressure to increase. The Increase in blood pressure brought about by this reflex may be enough to overcome the intraocular pressure; blood flow returns to the retina, and vision returns. A time lag of about 4 to 6 s between blackout and return of vision is required by this reflex mechanism.

Centrifuge studies have shown that the effects of +-Gx on the cardiovascular system are diminished when compared to +-Gz. During transverse acceleration, subjects have withstood +15 Gx without blackout, but performance capabilities are impaired at levels as low as +5 Gz, when it becomes impossible to raise the head or the arms against the high G-force. Some limb movement can be achieved between 5 to 9 G, but it is restricted. It may be impossible for a pilot to reach forward and activate a switch located on the instrument panel. Minimal movement using wrists and fingers is possible and can be accomplished if the arm is not required to be moved from the armrest.

The adverse effects of the increased weight on the body components are most clearly shown by the cardiovascular system. The blood stream is supported by elastic blood vessels and depends upon specific pressures for normal function. Excessive acceleration causes gross disturbances in the distribution of pressures and volumes within the system.

These effects are especially pronounced when a subject is exposed to prolonged +Gz and -Gz accelerations and can be explained by the effects of gravity on the body as observed in Figure 7.1.4-1. In this example, a 6-ft (182-cm) man standing upright exposes a 57-in. (145-cm) column of blood from the heart to the feet to the effects of +1Gz. Because of its weight, this column of blood exerts a hydrostatic pressure of 113 mmHg in addition to the normal arterial pressure in the feet. For a man with a mean blood pressure of 100 mmHg at heart level, the mean arterial blood pressure in the feet would be 213 mmHg. When the subject is in the upright position, this hydrostatic pressure passively distends the blood vessels of the legs and results in an additional 0.53 qt (0.5 L) of blood being pooled within the feet and legs. Each additional +Gz unit increases the blood pressure at foot level another 113 mmHg, resulting in more blood being pooled in the lower extremities. This redistribution of blood within the body reduces the volume of circulating blood available to supply the body's

requirements. In Figure 7.1.4-1, blood pressure above the heart is reduced by hydrostatic pressure. Under conditions of +1 Gz, the 12-in. (30-cm) fluid column from the heart to the brain exerts a hydrostatic pressure of 23 mmHg.

Therefore, if the mean blood pressure at the heart is 100 mmHg, the pressure at the level of the brain will be 77 mmHg. For each additional +Gz, the blood pressure at brain level would be reduced another 23 mmHg, eventually producing stagnant hypoxia.

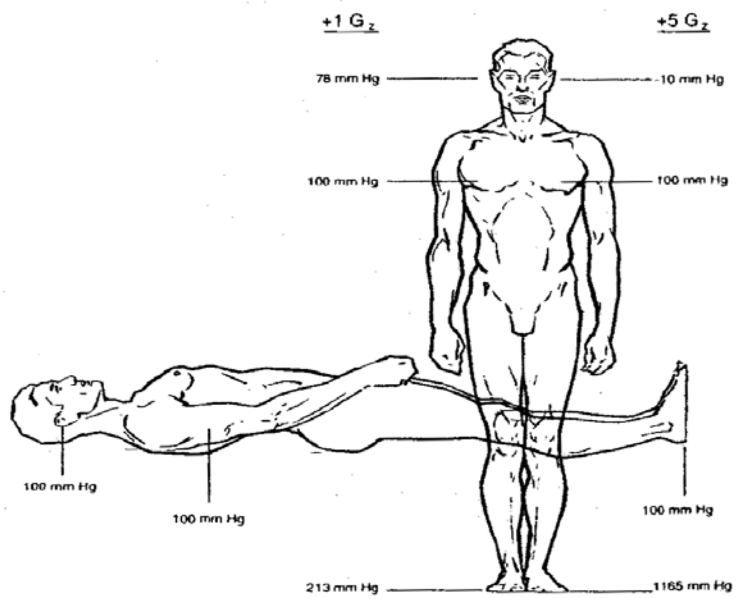

Figure 7.1.4-1. Schematic of the Hydrostatic Blood Pressure in the Supine Position and Erect Position at +1 Gz and +5 Gz

Figure 7.1.4-1 illustrates the hydrostatic effects on the arterial blood pressure of a person in an upright and supine position undergoing an accelerative force of +5 G_z. In the supine man, the blood pressure at head level is 100 mmHg as is the blood pressure in the feet. In the upright man, blood pressure at eye level is 78 mmHg at 1 G and 10 mmHg at 5 G. In general, forces lasting less than 2 s have little effect on the cardiovascular system. Embarrassment of the cardiovascular system is man's limiting factor when exposed to prolonged +Gz accelerations.

Numerous cardiovascular symptoms have been noted under G stress. These symptoms include grayout, blackout, loss of consciousness with accompanying seizures, convulsions, amnesia and confusion, cardiac dysrhythmias (tachycardia and bradycardia), heart blocks, and stress cardiomyopathy. The easiest way to understand many of the basic cardiovascular effects of G is to model human circulation as a simple hydrostatic column. The important parameters are the height of the column, the pressures within the column, and the density of the fluid affected. For all practical purposes, this model is a good representation o the body's response to rapid onset, short duration +Gz stress. Assuming this model, the hydrostatic pressure at any point in the circulation can be predicted using the following formula:

$$PH = h\ d\ G$$

where PH is the pressure (in mmHg), h is the height of the column, d is the specific density of blood, and G is the accelerative force in G.

The hydrostatic column that is of most interest is between the heart and the brain. The brain is approximately 340 mm above the heart. The specific density of blood with respect to mercury is 1/13.6. Therefore, at 1G there is a hydrostatic pressure gradient (PH) of:

$$PH = 340 \text{ mm} \times (1/13.6) \times 1 = 25 \text{ mmHg}$$

If one assumes an average heart level systolic blood pressure (Pa) of 120 mmHg, then the brain level blood pressure is 120 – 25 = 95 mmHg. At 5 G, the PH of 125 mmHg will exceed the average Pa of 120 mmHg, and the lack of blood will cause unconsciousness. To understand the phenomenon of "blackout," one needs to remember that the average intraocular pressure is 20 mmHg. This intraocular pressure is the pressure the retinal artery must overcome to supply oxygenated blood to the retina. "Grayout" occurs as the retinal artery pressure in the periphery can no longer overcome the intraocular pressure and the blood flow to the peripheral retina ceases. Blackout is explained by the complete lack of blood flow to the eye, which causes it to cease to function before the brain shuts down. Blackout will precede unconsciousness by about 0.8 +Gz (20 mmHg/25 mmHg). The model outlined here does not adequately explain the cardiovascular response to gradual onset +Gz because the cardiovascular reflexes can compensate for the changes caused by +Gz stress. These reflexes will also play a role in the response to rapid onset G after 6 to 10 s of exposure. The reflexes, which are mediated by the carotid artery and aortic arch baroreceptors, result in increased sympathetic discharge and a resulting increase in cardiac rate, vasoconstriction, and venoconstriction and an increase in cardiac contractile forces.

An increase in heart rate has been one of the generally observed responses to +Gz. The response has been highly variable due to individual variation, physiological stress, and the amount of muscular straining being performed by the subject. The amount of absolute increase in heart rate is affected by the maximum G level reached and the rate at which the G was applied. Occasionally, individuals have been observed to have paradoxical bradycardia at high G levels. This finding is thought to be a sign of cardiac decompensation and is grounds for halting the G exposure. The heart-rate response to G has not been shown to be predictive of G-tolerance. Cardiac output has been noted to transiently increase under +Gz. The measurement of cardiac output under increased G load is difficult. It has been shown that there is a decrease in venous return under high G loads, which decreases the preload to the heart. So, despite the increase in heart rate, most authors believe that cardiac output is, at best, maintained under high G and that the output probably decreases in most cases.

The rhythm disturbances seen under +Gz have been of great aeromedical interest. There has been and continues to be debate on the significance of these observations. In asymptomatic and otherwise healthy individuals, these dysrhythmias are probably benign. Three specific dysrhythmias cause particular concern because of the potential for sudden incapacitation. The dysrhythmias are sinoatrial (S-A), atrioventricular (AV) dissociation, and ventricular tachycardia. Table 7.1.4-1 summarizes a 3-yr history of acceleration-related dysrhythmias observed in healthy subjects on the USAFSAM centrifuge (Leverett & Whinnery, 1985).

Table 7.1.4-1. Three-yr History of Acceleration-Related Dysrhythmias at USAFSAM[a]

Rank	Occurrences	Dysrhythmia Description
1	1,566	Sinus arrhythmia (rating varying >25 bpm)
2	1,073	Premature ventricular contractions (PVCs)
3	768	Premature arterial contractions
4	546	Sinus bradycardia (rate <60 bpm)
5	372	Ectopic atrial rhythm
6	272	Premature junctional contractions
7	171	PVCs with bigeminy/trigeminy
8	126	Multiform PVCs
9	104	AV dissociation
10	104	Paired PVCs

[a]Based on the exposure of 544 different individuals exposed to 9,831 +Gz runs (Leverett & Whinnery, 1985).

Many of the foregoing observations on cardiovascular response to +Gz were based on observations of response to one-time exposures to +Gz on the centrifuge. Recent research work has been concentrated on the response to multiple +Gz exposures and the effects of fatigue on this response. Generally, heart-rate response is dependent on +Gz level, but it also appears to be related to the blood lactate level, which is an indication of the amount of anaerobic work involved in resisting the effects of +Gz and the performance of the anti-G straining maneuver (AGSM) (Burton et.al., 1987). This ability to perform anaerobic work may explain the observed effects of physical training regimens on aerial combat maneuvering G-tolerance (Epperson et al., 1982; Epperson et al., 1985; Burton, 1986).

7.1.5. Respiratory Effects

During positive G or +Gz, the increased weight of the viscera pulls the diaphragm down, increases the thoracic volume, and disturbs the mechanics of respiration. The major physiologic effects of +Gz on pulmonary function can be summarized as (a) altered ventilation/perfusion ratios resulting in hypoxemia, (b) airway closure, and (c) atelectasis (Banks et al., 2008). There is also concern that exposures above 9 +Gz may result in pathophysiologic changes such as a compromise of chest wall mechanics, pulmonary edema, and disruption of anatomical integrity of the lung (Banks et al., 2008).

Observations of pulmonary function during increased +Gz have shown an increased respiratory rate, an increased tidal volume (limited at the upper +Gz by the G-force and the compression on the G suit), and an increased physiologic dead space. As a result, the $PaCO_2$ changes very little with increasing G stress (Banks et al., 2008).

Through a reflex mechanism, the respiratory rate is increased to almost double its resting value when G loads as low as +3 Gz are encountered. As the G loads are increased, fast, shallow breathing occurs. This leads to ineffective respiration and can result in hypoxic hypoxia. Increased +Gz loads also produce an increased ventilation/perfusion ratio in the upper portions of the lung. In the lower portions of the lungs, this ratio is decreased. The net result is an impaired ability of the lung to oxygenate blood.

The hydrostatic theory just explained would predict that at a higher +Gz there would be less perfusion of the upper areas of the lung and that at higher –Gz there would be more. This theory has been nicely demonstrated in a study of perfusion scans of the lung at various Gz levels (Whinnery, 1980). Similar ventilation-perfusion (V/Q) inequalities would be expected from G exposure along the axes, and this has been observed (Banks et al., 2008; Popplow et al., 1983).

Positive pressure breathing systems, straining maneuvers, and inflated anti-G garments also influence the breathing patterns in man during flight. With +Gx forces above +8 Gx, respiration is mechanically impeded due to a number of factors: the pressure of the viscera on the diaphragm, attempting to inspire against the increased chest weight, and the gross distortion of the nose and mouth. During +/-Gx, embarrassment of the respiratory system appears to be the most important limiting factor.

Acceleration atelectasis is a collapse of alveoli in the dependent lung caused by absorption of the alveolar gas. It has been associated with symptoms of cough, chest pain, and dyspnea. Acceleration atelectasis has been observed to be exacerbated by breathing 100% oxygen and by the use of the anti-G suit (Tacker et al., 1987). It has been shown that the absorption atelectasis produced by +Gz exposure can be reduced progressively with the addition of an inert gas (N_2) into the breathing mixture until it is almost entirely prevented with a mixture of 40% N_2 by the use of unassisted positive pressure breathing (PPB) and the anti-G straining maneuver (AGSM) (Tacker et al., 1987). Acceleration atelectasis has been one of the reasons diluter demand regulators have been favored by the USAF. The use of an onboard oxygen generating system (OBOGS) or more appropriately a molecular sieve oxygen generating system (MSOGS) in new-generation fighter aircraft that provides 95% oxygen on a continuous basis has prompted concern that acceleration atelectasis may become an operational problem of some significance (Tacker et al., 1987).

7.1.6. Renal System Effects

Decreases in renal blood flow observed when humans stand upright and when they exercise make it reasonable to predict that +Gz stress would decrease renal blood flow. Although this prediction has not been investigated in man, animal models confirm this prediction (Banks et al., 2008). Oliguria has been noted in humans, and increased levels of plasma rennin have been measured at +2 and +2.5 Gz (Banks et al., 2008). Further work on this area may be useful, as even small deficits of water and sodium balance have been associated with decreased +Gz tolerance.

7.1.7. Musculoskeletal Effects

Back, neck, and limb problems are the most frequently reported musculoskeletal problems. There are reported cases of intervertebral disk ruptures under high +Gz and many complaints of sore necks after the centrifuge rides and flights in high-G aircraft. Permanent injury is rare enough to warrant a case report.

7.1.8. Central Nervous System Effects

The observed central nervous system (CNS) effects are explainable by the effect of G on the cerebral circulation.

7.1.9. Visual Effects

Impairment of vision is one of the consequences of exposure to +Gz. Because of hydrostatic pressure, there is a decrease in the blood pressure in areas above the heart when +Gz is applied. The driving power or systolic pressure supplying blood to the brain is reduced approximately 23 mmHg for each +Gz exerted. The first effect of this decreased blood pressure is impairment of vision. For a subject in a relaxed condition and unprotected by an anti-G suit, loss of peripheral vision and reduction of visual acuity (grayout) occur at levels of +3 to +4 Gz. When G-forces reach +3.5 to +4.5 Gz, vision is lost and blackout occurs. At this point, the subject is still conscious and can hear and respond to questions. Blackout occurs before unconsciousness because the intraocular pressure of 16 to 20 mmHg reduces the driving power of the blood to the eye.

Human centrifuge experiments have proven visual acuity decreases progressively as the magnitude of the acceleration increases. Then changes in acuity cannot be completely accounted for in terms of reduced circulation to the eye and brain. One possible explanation is that these changes result from displacement of the crystalline lens of the eye in the direction of the G-force.

Another visual effect of acceleration is the decreased response to the retina to the same illumination level of light. The adverse effect of acceleration on the ability of the pilot to read the instruments in a night-lighted cockpit may be so pronounced that it results in reading errors.

Col (Dr.) Rick Allnutt discovered changes to the human color vision system under sustained G while riding in the DES centrifuge at Wright-Patterson AFB in the late 1990s. Allnutt found centrifuge subjects experienced a shift in hue from light blue to white and green to yellow as they observed a color chart at or near central light loss of vision under G (Allnutt & Tripp, 1998). Dr. Tamara Chelette (2000) investigated colorimetric factors under sustained acceleration including luminance, contrast ratio, saturation, wavelength, display techniques, and individual variability. Balldin (2000) found hue shifts in subjects exposed to 7 to 9 Gz. Balldin observed yellow hues shifting to yellow-red, red hues shifting to red-yellow, and green shifting towards yellow. These results indicate the ability to correctly identify the basic colors at high Gz may be impaired. The physiological basis of this phenomenon has never been confirmed. It is apparently due to a hypoxic effect at the eye-brain level. The implications on cockpit color display design in high-performance aircraft are obvious.

During lateral acceleration experiments in the DES centrifuge, it was observed that subjects lost vision in one eye relative to the other when exposed to both increasing +Gz as well as lateral Gy. It was noticed subjects were reporting the loss of vision in one eye before the other during an agile aircraft experiment on the DES. This is the first report of this phenomenon, since most combined axes experiments in the past did not have loss of eye level blood pressure with increasing +Gz as the end point. This phenomenon, called temporary monocular vision, can occur in aircraft with thrust-vectoring capability or canards that allow the aircraft to slip laterally while turning and pulling G (Allnutt, 2000).

Visual disturbances, such as blurring and excessive flow of tears, have been noted above +12 Gx. The decrease in vision above +12 Gx may, in part, be attributed to eyeball distortion caused by the large force acting on the anterior of the eye. Above +8 Gx, respiration becomes increasingly difficult because the rib cage becomes more and more fixed in the expiratory position, and diaphragmatic breathing is required to maintain sufficient air exchange. Some subjects have been able to withstand transverse acceleration of +26 Gx for several seconds with complete post-run recovery. Some subjects, immersed in water and protected with positive pressure breathing, have endured exposures of over +30 Gx. Painful respiration is usually the limiting factor in human tolerance to +/-Gx, and time tolerance at various levels of acceleration is usually defined by this difficulty in breathing.

7.1.10. Vestibular Effects

The vestibular apparatus of the inner ear plays an important role in spatial orientation and balance. The otoliths are stimulated by gravity and linear accelerative forces to give the flyer a sense of direction; the semicircular canals respond to angular accelerations to give the flyer another sense of direction. Accelerative forces in flight may influence the vestibular apparatus and induce disorientation. There are several illusions that can be generated when G > 1 (see section 7.3).

The somatogravic illusion is the classic “pitch up” or “pitch down” illusion. When + or -Gx is generated during flight, the otoliths of the vestibular system can be stimulated; since we normally sense this stimulation and relate it to head tilts at 1 G, a pilot can falsely perceive a +Gx exposure in the absence of good visual cues as a head tilt upward, or pitch up. Pilots may incorrectly pitch their aircraft down based on this false perception. When decelerating or experiencing –Gx, the opposite effect can be perceived.

The G-excess illusion is similar to the somatogravic illusion but typically occurs when G > 1 and the pilot is looking out of the cockpit, such as during formation flight. If G >1 and the pilot’s head is tilted up, the otoliths will slide further aft than when G = 1. This “excess” slide can be interpreted by the brain as a false pitch up; to correct this perception, pilots may pitch the nose of the aircraft down and drop the wing. These maneuvers can result in a mishap.

7.1.11. G-Tolerance

The human tolerance to acceleration has been the subject of much research. This research has traditionally looked at the relaxed tolerance of subjects to single exposures of +Gz and the absolute level of +Gz the subject is able to withstand. This research has defined the limits of G-tolerance in the z axis very well. The limits of G-tolerance in the other axes are not so well defined. More recently there had been increasing interest in repeated exposures to multiple +Gz levels for varying time courses. The purpose of this research would be to define the other parameter in G-tolerance, namely, that of durations of tolerance and the various endpoints that have been used by researchers in their experiments.

The accelerative forces acting at right angles to the long axis of the body, chest-to-back or back-to-chest direction, are annotated by the symbol +/-Gx. The transverse position of the body shown in Figure 7.1.4-1 provides the greatest tolerance to acceleration because of the limited hydrostatic effect on a blood pressure.

Research studies have been directed toward increasing human tolerance to accelerative forces. The main thrust of these investigations has been to develop methods to maintain an adequate eye-level blood pressure.

7.1.11.1 Blood Pressure. No correlation has been found between chronic high blood pressure and high G-tolerance, although higher blood systolic and/or diastolic blood pressure appears to aid G-tolerance (Webb et al., 1991). When fear or excitement cause blood pressure and heart rate to be elevated, improved G-tolerance results. The reason is that a greater G force is necessary to reduce the blood pressure to the point where cerebral blood flow ceases.

7.1.11.2 Body Position and Seat Back Angles. The simplest and most effective means of increasing tolerance to +Gz acceleration is to change the position of the body's long axis relative to the inertial force. The intent is to reduce the vertical height of the hydrostatic column of blood extending from the heart to the eyes. To obtain maximum tolerance to +Gz, it is necessary to tilt the subject to 60° to bring the eyes level with the heart.

In Figure 7.1.4-1, the heart-eye distance in the standing and supine posture is compared with other body positions. Short of full prone or full supine positions, the semi-kneeling position would offer the most protection with no gross symptoms to approximately +10 Gz. A backward tilt of about 45° is required to significantly increase the blackout threshold, while a backward tilt of 30° exists in the F-16 aircraft. The F-15 seat is tilted 12.5° from the vertical, the F/A-22 is tilted 14.5°, and the JSF (F-35) is adjustable from 12-17.5° from vertical.

7.1.11.3 M-1 Maneuver. The M-1 maneuver is a straining technique that improves G-tolerance. It was named M after the Mayo Clinic, where it was developed by Dr. Earl Wood. Pilots refer to the M-l maneuver as the "grunt" maneuver since it approximates straining to lift a heavy weight. The M-1 maneuver consists of leaning forward at the hips, slowly and forcefully exhaling through a partially closed glottis, and, simultaneously, forcefully contracting all skeletal muscles. Leaning forward gives some degree of circulatory protection, the pressure within the chest is increased by strong muscular contraction against a partially closed glottis, and the contraction of voluntary muscles externally compresses and reduces blood pooling. For the best results, slow exhalation must be repeated every 4 to 5 s.

Properly executed, the M-1 maneuver results in a fluctuating intrathoracic pressure of 50 to 100 mmHg, which raises the arterial blood pressure and increases +Gz tolerance about 2 G. Human centrifuge subjects wearing anti-G suits, who have been instructed in the correct performance of the M-1 maneuver, have been able to withstand +9 Gz for 60 s and longer without visual symptoms.

An aircrew member may obtain equal protection from either the M-1 maneuver or by attempting to exhale against a closed glottis if he/she also simultaneously contracts all skeletal muscles. This variation is called the L-1 maneuver.

7.1.11.4 L-1 Maneuver. This G straining maneuver was developed by Dr. Sidney Leverett, thus the L nomenclature. Equivalent protection is provided by each of the maneuvers both with and without the anti-G suit. The L-1 maneuver is preferred by most aircrew today as it is easier on the throat and larynx. Forcefully exhaling against a closed glottis without vigorous skeletal muscle tensing can lead to an episode of

unconsciousness at relatively low G levels. Therefore, instruction on the proper method of performing the straining maneuver is essential. [Note: Anti-G suits are discussed in section 6.2.]

7.1.11.5 Individual Variations in Tolerance to +Gz. In discussing the physiological effects of G-forces, a range of +Gz acceleration was expressed for a particular effect. It was stated that grayout occurs at an average value of +3 to +4 Gz. Because of individual differences in heart-to-head distance, blood pressure, muscle tone, and venous return, the true range might be 2.2 to 7.1 G.

7.1.11.6 Factors Decreasing Tolerance to +Gz. Any factor that reduces the overall efficiency of the body, especially if it reduces the reserve of the circulatory system, causes a marked reduction in man's tolerance to G. Although not correlated with GLOC or predictability of G-tolerance, the following anthropometric/physiologic parameters were associated with higher G-tolerance during pilot training on the USAFSAM centrifuge at Brooks AFB, TX (Webb et al., 1991):

- Greater age
- Lower height
- Lower height/weight ratio
- Higher systolic and/or diastolic blood pressure

An example of self-imposed stress is the lowered tolerance caused by an alcohol hangover. Several abnormalities exist that would preclude the individual from being exposed to greater than +1 Gz: varicose veins; hemorrhoids; hernia; and eye disorders, especially glaucoma.

Early research in +Gz tolerance attempted to define the point of unconsciousness. As the understanding of the response to G became more refined, "blackout" or visual loss was used as the endpoint in human research. The modern concept defines +Gz in terms of the rate of acceleration, whether it be rapid (>0.33 G/s) onset or gradual onset, and the point at which there is peripheral light loss or the point of central light loss.

7.1.11.7 Body Position of Pilots and Crew in Relation to Accelerative (G) Forces. Since man can tolerate much higher G-forces when applied in the transverse direction, attempts have been made to alter pilot and crew stations to tilt back positions in the aircraft. This reduces the eye-to-heart hydrostatic column and exposes the pilot to +Gx and +Gz during combat maneuvering. Fighter aircraft such as the F-16 have a reclined seat at 30° from the vertical, and the F-35 can recline the seat to 17.5°.

Research at USAFSAM (Brooks City-Base) has used three kinds of centrifuge runs to evaluate G-tolerance. The gradual onset run (GOR) is conducted at 0.1 G/s, the rapid onset run (ROR) at 1 G/s, and very high onset G (VHOG) at 6 G/s. The GOR evaluates the body's baroreceptor response to G, as the cardiovascular responses have time to be effective. The RORs and the VHOGs are more representative of the type of G-onset profiles that aircrew are likely to experience in the F-15, F-16, and F-22 generation of aircraft. This kind of research on normal unprotected subjects has resulted in the data found in Figure 7.1.11-1.

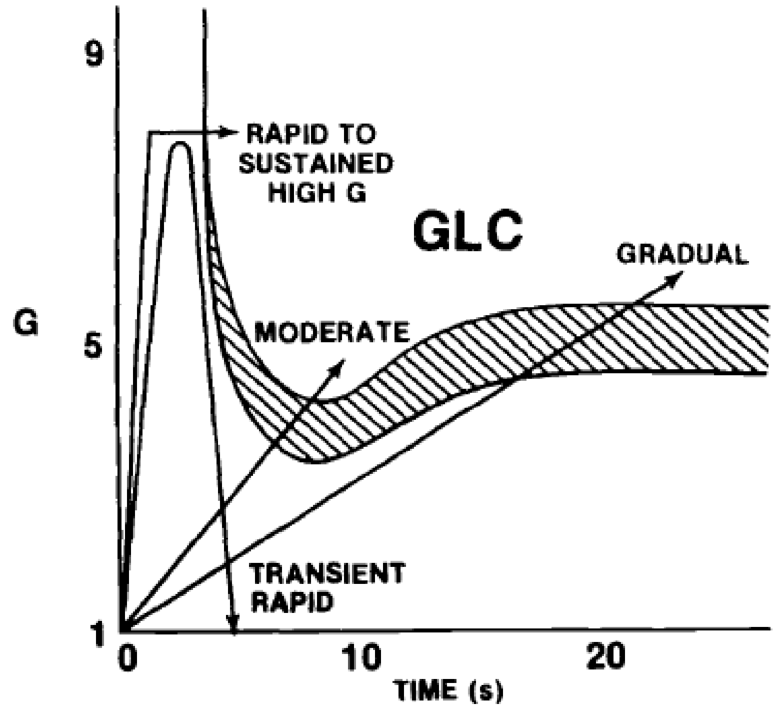

Figure 7.1.11-1. G-Time Tolerance Curve (Gillingham & Fosdick, 1988)

The G-Time Tolerance Curve (Stoll, 1956) (Fig. 7.1.11-1) models the response of a human with no previous G exposure. Modifications in the curve occur if a negative G exposure is followed by a +Gz exposure resulting in what has been termed the push-pull effect (Banks et al., 2008). The push-pull effect has been implicated in a number of GLOC mishaps (Banks, 1994). During repeated exposure to +Gz in a high-performance aircraft, it is common practice to push negative Gz while regaining aircraft energy prior to another high G turn. During this period of negative G, which may last only 1 or 2 s, there is a rapid development of bradycardia, peripheral vasodilation, and the likelihood of cardiac arrhythmias. The push-pull effect occurs when the pilot pulls positive G giving rise to profound changes in cerebral perfusion and a marked reduction in +Gz tolerance (Prior, 1995). A good anti-G straining maneuver and an operating anti-G suit reduce the magnitude of the push-pull effect, but a significant lowering of G-tolerance remains.

As discussed in the section on cardiovascular effects, the simulated aerial combat maneuver has been used to evaluate longer duration tolerance to +Gz stress and to evaluate the fatigability of G-tolerance. This research shows that the work of being at high +Gz is anaerobic and that understanding human performance and endurance at high +Gz is best related to isometric exercise physiology and to anaerobic metabolism (Burton et al., 1987).

7.1.12. G-Induced Loss of Consciousness

Unconsciousness occurs at G levels slightly higher than those that produce blackout and is produced in most unprotected individuals when 4.5 to 6 +Gz is exerted for more than 6 s. It occurs when the effective blood pressure at the level of the brain is reduced to the point where inadequate blood flow and unoxygenated blood from impaired respiration cause both stagnant and hypoxic hypoxia.

This combination is probably the reason for the long recovery period, which may take up to 1 min following the end of the acceleration. A period of disorientation may also be present for some time after consciousness is regained. During this period of disorientation, the individual is unaware of his/her surroundings--a poor situation for a pilot during low level flight or in an air combat environment.

G-induced loss of consciousness (GLOC) has become a major issue of research and operational interest. The USAFSAM definition of GLOC is “a state of altered perception wherein (one’s) awareness of reality is absent as a result of sudden, critical reduction of cerebral blood circulation caused by increased G forces” (Burton, 1988). Although centrifuge subjects apparently recovered from the total incapacitation period of GLOC in less than 30 s, Tripp et al. (2006) found that their cognitive performance scores on a tracking and math task never returned to pre-GLOC levels for an additional 30 s after recovery.

The loss of aircraft and aircrew are, of course, a major concern, but every GLOC episode does not result in a loss of an aircraft. Surveys by the USAF and the U.S. Navy indicate that the pilot population in the fighter-attack-trainer is reporting about a 12%-14% incidence of GLOC (Johanson and Pheeny, 1988). Full function of higher levels of cognitive processing may not be restored for several minutes or more. The brain is not an on-or-off organ and, in fact, comes on in stages. This is most significant to fighter pilots in combat, since statistics show that a majority of the GLOCs occur during defensive maneuvering against airborne threats. These higher cognitive levels are used when the fighter pilot processes information in basic flight maneuvers (or dog fighting) and defensive maneuvers against surface-to-air missiles and anti-aircraft artillery. If a fighter pilot were engaged in actual combat and experienced GLOC, it is quite probable that he/she would not survive, as he/she would be a nonmaneuvering target for 12-24 s on the average and then not a “full up” fighter pilot for possibly several more minutes—very easy target to kill. The work of Whinnery on the occurrence of amnesia in GLOC suggests that at least half of the pilots will not recall an incident of GLOC, so the incidence may be as high as 24%, with occurrence rates on aircraft such as the F-18 of 9.3 incidents per 10,000 flying hours (Johanson and Pheeny, 1988; Whinnery, 1988). This is obviously an issue of major operational concern.
Research on the degree of incapacitation caused by GLOC has indicated that there is an average total (unconsciousness) time of 15 s followed by a period of relative incapacitation (confusion and disorientation) of 12 to 15 s, resulting in a total time of incapacitation of between 24 and 37 s (Whinnery, 1988).

Several studies indicate that most GLOCs are accompanied by involuntary movements (funky chicken, etc.). Although not thoroughly studied, the origin of these movements is thought to be the brain-stem reticular formation. As blood flow to the brain returns after the G load is reduced, differential reperfusion allows the reticular formation to become tonically active, causing involuntary movements of many of the skeletal muscles throughout the body. These involuntary movements last for an average of 4 s and cease at the end of the absolute incapacitation period. Involuntary movements generally occur during “deeper” GLOC episodes and can cause unintentional actuation of switches and controls by the pilot. Involuntary movements during GLOC have been responsible for inadvertent throttle reduction and gear lowering at high speeds.

One final point concerning the GLOC phenomenon: one might assume that because the eyes tend to fail at lower G levels than does the brain, aircrew should receive sufficient warning (problems with vision first) and could avoid GLOC. However,

such is not always the case. If the pilot rapidly increases and maintains the applied aircraft G forces above his tolerance level for longer than oxygen reserve in the brain can supply the eyes and functional areas of the brain (the oxygen reserve is the same for both), simultaneous failure of vision and consciousness can occur; the progression from grayout to blackout to GLOC would effectively be a single event. Thus, there will not be any visual warning of the impending GLOC.

Several protective strategies to increase G-tolerance and to prevent GLOC have been explored. These strategies include centrifuge training, weight training, new G suits and G valves, altering the seat back angle in the aircraft, and the use of positive pressure breathing both assisted (with counterpressure) and unassisted.

Centrifuge training has been received with enthusiasm by all those who have experienced it. Most major North Atlantic Treaty Organization (NATO) air forces, including the USAF, either have centrifuge training programs or are developing them (Gillingham and Fosdick, 1988). These programs usually consist of 1 day of lectures on the physiology of G, a GOR run in the centrifuge, followed by several ROR to a maximum of 9 +Gz (Gillingham and Fosdick, 1988).

The work on G-valves for inflating G suits has revolved around the need for faster inflation rates with high flow valves, variable inflation rates that match the G-onset profile, and the use of "smart" microprocessor-controlled systems that may pulse the pressure in the suit to "milk" the venous return from the legs (Van Patten, 1988).

The first workable anti-G suit was developed by Franks in Canada during World War II (Gell, 1961). The suit was not acceptable operationally because it was water filled, but it laid the groundwork for what was to follow. The current USAF anti-G suit is the CSU 3-B/P, which has calf, thigh, and abdominal air bladders that can be inflated to a maximum of 10.0 psi. This suit must be individually fitted and provides about 1 +Gz of protection. Most of the protection seems to be provided by the abdominal pressure bladder or the combination of all the bladders, as inflation of the leg bladder alone only provides a 0.2 increase in +Gz tolerance (Banks et al., 2008).

The use of reclined seats to increase G-tolerance has been incorporated into the F-16, which has an inclined seat of about 30°. Most research would suggest that there is no significant increase in G-tolerance until the seat is inclined 45°. Experimental work has shown great potential for this technique, but at present the practical problems of incorporating supinating seats into the cockpit have not yet been solved (Burns, 1988).

Positive pressure breathing with chest counterpressure has been shown to increase G-tolerance only about 0.5 +Gz, but it has had significant fatigue reduction effects (Burns, 1988). This technique, using 60 mmHg of breathing pressure above ambient pressure, has been incorporated into the combined advanced technology enhanced G-ensemble (COMBAT EDGE), which is a combination G suit, chest counterpressure jerkin, and higher pressure mask.

One other area of "GLOC protection" is the development of an auto recovery system. The current generation of fly-by-wire aircraft can be flown by the mission computers without pilot input. If systems can be developed to correctly identify that a pilot has lost consciousness, the aircraft's computer can be programmed to recover the aircraft to straight and level flight. Problems with this concept at present are the unequivocal identification of the loss of consciousness (LOC), the provision of appropriate pilot override capability, and pilot acceptance of the machine doing the flying. While the problem of GLOC has not been entirely solved, the technology to solve many of the problems and the training to use technology are at hand.

7.1.13. -Gz Effects

When you stand on your head, a force of -1 Gz is experienced, and it becomes uncomfortable after several seconds. During –Gz, the blood is forced toward the head, causing congestion and swelling of the tissues above the level of the heart. Forces of -2 to -3 Gz cause extreme congestion in the tissues of the head and neck and produce the sensation that the eyes are bulging. The threshold limit of -Gz is in the range of -2.5 to -3.0 G for 7 to 10 s. Severe headaches and confusion may follow exposure to -Gz forces, which are of low magnitude and short in duration (several minutes).

Some aircrew members experience *red-out* under the influence of -Gz forces. This phenomenon has never been observed in the centrifuge and is difficult to explain physiologically. Red-out may be caused by light shining through the lower eyelid, which is sometimes forced up over the eye by -Gz. Since the blood vessels within the eyelids would be engorged with blood, light could be seen through the blood-filled eyelids, giving the impression a red curtain had been drawn over the eye. Some researchers believe that the red appearance may be due to increased pressure applied around the retinal area and optic nerve. In early acceleration literature, it was believed retinal damage would occur during -Gz maneuvers and would lead to blindness. However, aircrew members experiencing red-out during -Gz acceleration have had no retinal damage.

The increased blood pressures that occur in the head and neck during -Gz frequently rupture the small, thin-walled venules and capillaries in these areas. The eye is particularly prone to develop hemorrhages, which usually occur between the conjunctiva and the sclera. Vessels within the skull are not subject to ruptures since the cerebrospinal fluid pressure and venous pressure in the cranium are increased proportionately with the arterial blood pressure. This counterpressure protects the cerebral vessels from rupture.

As the pressure in the vessels of the neck increases during -Gz, the baroreceptor reflex causes a slowing of the heart and a dilation of the arterioles. This is an attempt to bring the arterial pressure back to normal and is the likely reason for the push-pull effect if followed by a +Gz exposure. If the G-force is severe, the heart may stop for 10 to 15 s. The reduced heart rate causes the arterial pressure to approach the venous pressure. As the pressure gradient across the capillaries declines, cerebral blood flow becomes slower. This may result in cerebral hypoxia when acceleration is prolonged.

No satisfactory methods have been devised for overcoming or reducing the effects of -Gz. The limit of human tolerance remains in the range of -2.5 to -3.0 Gz for 7 to 10 s. Normally, the endpoint for tolerance is the onset of a severe headache, and recovery follows within 24 hr after exposure. Flyers protect themselves from high -Gz acceleration by avoiding maneuvers that impose these forces.

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Concepts

G-tolerance
G-time tolerance curve
Law of Action and Reaction

Vocabulary

Acceleration
Acceleration atelectasis
+Gx acceleration (forward transverse G)
-Gx acceleration (backward transverse G)
+-Gy acceleration (right or left lateral G)
-Gz acceleration (negative G)
+Gz acceleration (positive G)
L-1
M-1

7.2. Physiologic Effects of Vibration

Henning E. vonGierke, D.Eng., and William B. Albery, Ph.D.

7.2.1. Definitions

7.2.1.1 Vibration. Vibration is generally defined as the motion of objects relative to a reference position, which is usually the object at rest (von Gierke et al., 1996). Vibration is a series of oscillations of velocity, an action that necessarily involves displacement and acceleration. Vibration is described relative to its effects on man in terms of frequency, intensity, (amplitude), direction (with respect to the anatomic axes), and duration of exposure.

7.2.1.2 Amplitude. Amplitude is the maximum displacement from a position of rest. Nonperiodic or random motions are usually expressed in terms of octave band or third-octave band frequency analyses, and the energy in the bands is expressed in terms of root-mean-square (rms) values; peak values or the crest factor (peak/rms) can be important variables for random vibration. For sinusoidal vibration, the rms value is 0.707 the maximum peak value. Vibration amplitudes can be referred to as displacement (in m) or velocity (m/s) but are usually expressed in terms of acceleration (m/s^2 or G, where 1 G = 9.81 m/s^2).

7.2.1.3 Direction. In addition to the three linear vectors outlined below, vibration can also have three rotational degrees-of-freedom known as pitch (rotation around the y axis), roll (rotation around the x axis), and yaw (rotation around the z axis).

7.2.2. Operational Vibration Exposures

Powered automotion in helicopters, automobiles, trucks, tanks, and motorcycles exposes operators to increasing acceleration magnitudes with a frequency range extending up to 100 Hz, depending on the roughness of the air/road/terrain and the vehicle speed. Similarly, ship-at-sea motions can extend from extremely low frequencies produced by ocean waves (below 0.1 Hz) to high frequencies in high-speed surface attack ships. Military exposures can extend over several hours per day. Flying, particularly military flying in high-performance combat aircraft, can increase sustained acceleration exposures up to 9 G during combat maneuvering. Exposure times range from a few seconds to up to 1 min. Potentially higher G levels are limited only by human tolerance considerations. Air combat maneuvers modulate these loads and change their direction with respect to the aircrew (Fig. 7.2.2-1). In addition, air turbulence can superimpose vibration and buffeting on these sustained accelerations. Low-altitude, high-speed flight in military operations (as well as air turbulence in commercial and general aviation) causes the most severe vibration exposures. In rotary wing aircraft, vibration frequencies are associated with revolution rates of rotors, gearboxes, and other engine or mechanical parts. The largest amplitude vibrations occur at main rotor blade frequencies and increase as speed loading increases and with increased power of the helicopter propeller system.

Figure 7.2.2-1 Vibration Axes during Combat Maneuvering

As human beings, we are accustomed to living 24 hr a day in the Earth's gravitational field (defined as a sustained 1 G acceleration). Upon this sustained gravitational field, our motions and activities superimpose accelerations of various amplitudes, frequencies, and durations; walking, running, and other physical activity expose the body to acceleration fluctuations with frequency components ranging from a fraction of a second to several cycles per second (Hz).

Operators and passengers of all types of transportation vehicles, in the air, space, on the ground, or underwater, are exposed to some kind of vibration during some phases of the operation. The oscillations of the vehicle motions around a reference stationary state, at rest, or during constant velocity and/or acceleration are transmitted to the occupants through the supporting seat and floor or through wall vibrations or vibrating handles. This transmission results in motions of the whole human body or body parts. In studying biochemical interaction, it is somewhat artificial to separate body motions into sustained, transient, rotational, or impact acceleration and linear oscillations, although this is driven, in part, by our analytic, experimental, and laboratory stimulation tools. In taking this conventional approach, it is important to keep its limitations in mind and not to forget that vibrations are only a small part of the total mechanical force or motion spectrum. The physical, physiologic, and performance effects to be discussed for the vibration spectrum of interest, from 0.5 Hz to a few hundred hertz, often occur simultaneous with and are modified by the effects of sustained and/or transient accelerations. Low-altitude, high-speed flight in military operations and storm and clear-air turbulence in commercial and general aviation cause the most severe vibration exposures of concern. Their severity depends on the input gust velocities and acceleration spectra, as well as on the aerodynamic properties and

flexibility of the aircraft. In military aircraft with manual or automatic terrain-following control systems, maneuvering loads with maxima between 0.01 and 0.1 Hz are superimposed on the gust-response spectra of the aircraft and crew.

Vibration environments are studied in the laboratory through the use of different types of vibration, or “shake,” tables. These types of acceleration and vibration laboratory simulations are limited with respect to emulating real-world six-degrees-of-freedom motion. There are few real-world operational investigations reported in the literature.

7.2.3. Pathophysiologic and Physiologic Effects of Vibration

There is no specific target area or organ for low-frequency, whole-body vibration, and the mechanical stresses imposed can potentially lead to interference with bodily functions and tissue damage in practically all parts of the body (Dupuis et al., 1986). Fortunately, operational stresses are almost never that high, and vibration exposures remain below injury and interference levels. Severe buffeting in one military aircraft led to a few oscillations best described as repetitive impacts that resulted in spinal fractures. Based on scanty human evidence and animal studies, damage to renal functions and pulmonary hemorrhages are suspected of being the first sign of injury from acute overexposure in the frequency range of maximum abdominal response (4 to 8 Hz). Whole-body vibration of intensities voluntarily tolerated by human subjects up to the limit of severe discomfort or pain has not resulted in demonstrable harm or injury (Lippert, 1963). Minor kidney injuries in truck and tractor drivers have been suspected to be due to vibration exposure of long duration at levels that produce no apparent acute effects, but epidemiologic studies have yet to prove any clear correlation. Similarly, higher incidents of back pain in helicopter pilots and tractor operators have been assumed to be related to the vibration produced by the vehicles; in spite of several studies and plausible arguments, clear dose-response relationships are lacking and difficult to obtain. Modern exposure limits for health and safety reasons are, therefore, primarily based on voluntary tolerance limits, pain thresholds, and experiences with occupational exposures assumed to be safe. Most physiologic effects in the 2- to 12-Hz frequency range are associated with the resonance of the thoracoabdominal viscera. It has been shown to be responsible for the pain occurring in the 1- to 2-Gz (peak) and 2- to 3-Gx ranges, suspected to be caused by the stretching of the perichondrium and periosteum at the chondrosternal and interchondral joint capsules and ligaments. Movement of abdominal viscera in and out of the thoracic cage, in both x- and z-axis excitation, is responsible for the interference of vibration with respiration. It causes the involuntary oscillation of a significant volume of air in and out of the lungs, leading to an increase in minute volume, alveolar ventilation, and oxygen consumption. In some experimental exposures to Gz vibrations, PCO_2 decreased, and clinical signs of hypocapnia were observed, suggesting hyperventilation. Dyspnea results from short exposures to high amplitudes.

Cardiovascular functions change similarly in response to x-axis, and y-axis, and z-axis excitation (Kent et al., 1986). In general, the combined cardiopulmonary response to vibration in the 2- to 12-Hz range resembles the response to exercise. Although the increased muscular effort of bracing against the vibration and psychologic factors may account for some of the response, observance of the same general pattern in anesthetized animals speaks for the stimulation of various mechanoreceptors.

The resonance of the abdominal viscera, with its resulting distortions and stretching, is also responsible for the epigastric or periumbilical discomfort and testicular pain reported at high amplitudes. Headache is frequently associated with exposure to frequencies above 10 Hz. Vibrations that are transmitted to the head directly from the headrest can lead to extremely uncomfortable and disturbing impacts of the head against the headrest. Raising the head away from the headrest and attempting to counteract the forces lead to neck muscle strain, spasm, and soreness. Restraining the head to follow the motion can result in disorientation during the exposure. Rubbing the body surfaces against the seat, backrest, or restraint straps (e.g., “back scrub” in some tractor or vehicle arrangements) can lead to discomfort and skin injuries.

The severe vibration responses and injuries observed in animal experiments have not been reported in humans due to appropriate safety criteria (ANSI, 1979; ANSI, 1983; ISO, 1985). In interpreting animal experiments, it is of utmost importance to consider appropriate scaling laws due to changed body dimensions and resonances; therefore, maximum-effects frequencies are considerably higher in small animals.

7.2.4. The Vibration Syndrome

The only specific vibration-induced disease with well-supported etiologic data is the vibration disease, or “white finger syndrome,” caused by habitual occupational exposure over months and years to the vibration of machinery and certain hand tools such as chain saws, chipping hammers, and other pneumatic tools (Taylor et al., 1975).

7.2.5. Effects on Vision

Difficulties in reading instruments and performing visual searches occur when vibrations introduce relative movement of the eye with respect to the target (Benson & Barnes, 1978; Griffin et al., 1978; Fig. 7.2.5-1). Although persons and instruments might be excited by the same structural vibrations, their response is completely different, causing different displacements in different frequency ranges. A complex relationship exists between all of the relevant parameters, such as vibration frequency, amplitude and direction, viewing distance, illumination, contrast, and the shape of the viewed object (Griffin et al., 1978). Large effects on the resolution of visual detail occur under z-axis, whole-body vibration and for y-axis and z-axis vibration of viewed objects. The main difference between the object versus the subject vibration is the compensating ocular reflexes mediated by the vestibular system (vestibulo-ocular reflex), which enable the eye to compensate for body and head motions, thereby fixating the gaze on the target (Griffin et al., 1978). Although effectiveness of the vestibulo-ocular reflex drops off about 1 Hz, the reflex has been shown to affect results up to 8 Hz. Analysis and prediction of visual capability are further complicated by the fact that translational body motion results not only in translational but also rotational head movements. The latter influences passive eye movement as well as vestibular feedback. The same compensatory reflexes have been shown to remarkably degrade visibility on head-mounted or helmet-mounted displays under vibration when the display moves with the head (Griffin et al., 1978). Although mechanical eye resonances have been investigated in several studies up to 90 Hz, their influence on vision is apparently of secondary importance, and no sharp resonance phenomena as a function of frequency have been observed.

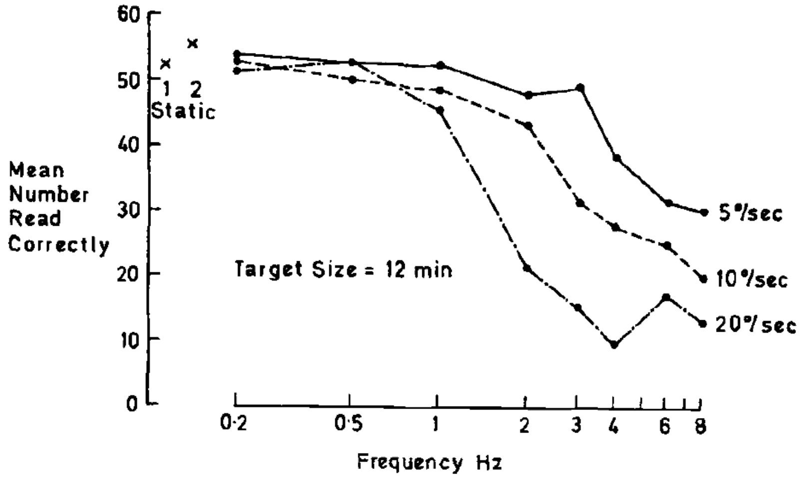

Figure 7.2.5-1. Visual Performance of Eight Subjects Required to Read a Display that Moved with the Head During Sinusoidal Angular Oscillation in Yaw at Peak Velocities of +0.09, 0.17, and 0.35 rad/s. Control measures (x) obtained with head and display static before (1) and after (2) exposure to angular oscillation. Target size refers to the subtended height of each digit of the 3-digit display (Benson & Barnes, 1978).

Unfortunately, the large number of test results cannot yet be presented in uniform curves allowing the prediction of visual decrement. The large number of variables prevents generalization of the results. These variables include, for example, small changes in subject posture and restraint, affecting translational and rotational head responses, and large intersubject intervariability among others.

For Gz +- Gx, Gy, and Gz vibrations and for Gx +- Gz vibrations, the largest effects were found in the 11- to 15-Hz range. Decoupling the head from the headrest improved capability in this frequency range, whereas head restraints generally reduced reading errors at 6 Hz and below. The type of helmet and restraint, however, is crucial for these experiments. All of these results underline the previously stated conclusion that because of the complexity and large number of variables, important vehicle performance requirements should be tested for each specific configuration in realistic simulations.

7.2.6. Vibrations Producing Motion Sickness

Although the symptoms and causes of and therapeutic measures for motion sickness are discussed in another chapter, the frequency and amplitude range of vibrations producing the discomfort or acute distress associated with motion sickness will be mentioned briefly in this chapter. The frequency range for vertical (z-axis) vibration leading to this disability extends downwards from 1 Hz on, i.e., it starts right below the frequency range so far discussed. Because vibration-caused motion sickness can occur in most transportation systems, and controlling vibrations in one frequency range can easily magnify the amplitudes in another frequency range, design guidance with respect to motion sickness will be mentioned here briefly. The absolute levels for severe discomfort after 30-min, 2-hr, and 8-hr exposures are very tentative and open to many variables. The boundaries as presented apply to infrequent,

inexperienced travelers and are assumed to cover approximately 95% of such a population (5% probably never adapt to motion below 1 Hz). Civil and military vehicle operators and many travelers clearly have much higher discomfort and tolerance thresholds due to habituation and selection.

7.2.7. Sustained Acceleration Combined with Vibration

Limited experimental evidence suggests that accelerations and vibrations are not synergistic. On the contrary, it appears as if vibration tolerance at 11 Hz 3 Gx was increased by the simultaneous application of 3.8 Gx. This finding can be theoretically explained by the inertial preload effect of the sustained acceleration, which at the same time has a static preload or restraining effect on the subject. On the other hand, it can be argued that the vibrations partially alleviate or counteract the circulatory and respiratory manifestations of sustained acceleration.

Whole-body vibration exposure can result in various pathologic and physiologic effects located in different body regions, which are determined by the exposure frequency. For most operational exposures, however, effects on task performance and interference with activities were found to be of primary concern. The only well-documented vibration-induced disease is the “white finger syndrome” caused by habitual exposure to vibrating hand tools. The standards for safety, performance capability, and comfort for whole-body vibration (1 to 80 Hz) and for risk assessment of hand-tool vibration (8 to 1000 Hz) were recommended as practical guidelines for the assessment of operational vibration exposure. The guidance for the evaluation of vibration in air, spacecraft, and other transportation vehicles was supplemented by weighting curves (0.1 to 0.63 Hz) to estimate the incidence of motion sickness in vertical vibrating motions. The information and references presented should be adequate for the evaluation of existing and future aerospace vibration problems (CHABA, 1987).

Impact forces of less than a second’s duration that occur under crash or emergency aircraft escape conditions are not considered in this chapter. Sustained acceleration environments are experimentally obtained on human centrifuges, where human performance during simulated aerospace missions has been studied extensively.

To fully capture the influence of acceleration or vibration on mission effectiveness, it is essential to simulate the real-world environment as closely as possible and to know the task requirements, the time of day during exposure, duration of exposure, repetition rates, and timing with respect to other stressors. These factors should be kept in mind during the discussion that follows.

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Vocabulary

Vibration
Amplitude

7.3. Spatial Disorientation

William Ercoline, Lt Col (USAF Ret), Andrew McKinley, and Brian Stanley

7.3.1. Introduction

Despite training and ongoing research efforts, spatial disorientation (SD or SDO) remains a significant factor in the death of aircrew and military members. Information presented in the following chapter is an attempt to provide an operational overview of one of the most serious but often ignored causes of human error associated with aircraft flight.

The failure of the pilot to correctly perceive the spatial orientation of his or her aircraft has always been a problem; unfortunately, it was never realized as such until 1927 (Ocker & Crane, 1932). Although more than 80 yr have passed since first being recognized as a pilot killer, the problem has not been eliminated. At the annual Aerospace Medical Association (AsMA) conference, accident rates are presented each year by the military branches in attendance. The statistics are alarming, and SD continues to account for several of the major Class A mishaps each and every year. There are several known countermeasures, but the one most promising is the instrument crosscheck. And although several technologies exist that are capable of making the instrument crosscheck more efficient for the pilot, such as audio and tactile feedback, few have been employed in modern military aircraft beyond the use of an alerting system. Before beginning a detailed analysis of SD causes and consequences, the following paragraph penned by Dr. Kent Gillingham, a distinguished USAF SD scientist and researcher, is provided that discusses the physiologic origin of human SD in aviation.

> The evolution of humans saw us develop over millions of years as an aquatic, terrestrial, and even arboreal creature, but never an aerial one. During this development humans were subjected to many different varieties of transient motions, but not to relatively sustained linear and angular accelerations commonly experienced in aviation. As a result, humans acquired sensory systems well suited to maneuvering under our own power on the surface of the Earth but poorly suited for flying. Even birds, whose primary mode of locomotion is flying, are unable to maintain spatial orientation and safe flight when deprived of vision by fog or clouds. Only bats seem to have developed the ability to fly without vision by replacing vision with auditory echolocation. Considering our phylogenetic heritage, it should come as no surprise that our sudden entry into the aerial environment resulted in a mismatch between the orientational demands of the new environment and our innate ability to orient. The manifestation of this mismatch is spatial disorientation. (Gillingham, 1993)

While Dr. Gillingham's rationale for spatial disorientation causes should not be surprising, the phenomenon involves a complex relationship between human physiology and perception (both visual and somatosensory) that can be challenging to fully alleviate and to fully appreciate. However, it is important for all individuals in aerospace careers to gain an appreciation of the definitions, illusions, and known countermeasures of SD. Such knowledge contributes to future SD countermeasures, the identification of

SD risks, and the development of habits that can aid in the prevention of SD. Although motion sickness is not analogous to spatial disorientation, the two are related by way of their physiological mechanisms. A section at the end of the chapter has been provided to better appreciate the relationship of motion sickness to SD. This chapter is primarily devoted to the causes of SD and the various SD illusions that have been reported over the many years of man's attempt to conquer his aerial environment. It is recommended that should the reader want more insight into the physiology and psychology associated with SD, he or she should read any of the aerospace medicine books currently on the market or the unique text titled "SD in Aviation" published by the American Institute of Aeronautics and Astronautics (Previc & Ercoline, 2004).

7.3.2. Definitions

Let us take a stepwise approach to the more complex term of SD. We'll start with the fundamental definition used throughout the chapter and then develop the more commonly known definition used throughout the research community.

7.3.3. Illusion

An illusion is a false impression or misconception with respect to actual conditions, better known as reality. Visual illusions are perhaps the most prominent and deceptive causes of SD. Think of all the times you have seen something that looked to be true but upon closer inspection it turned out to be false, e.g., a mirage, a magic trick, the perception of motion. Amusement parks are loaded with these types of illusions, and artists try to capture many visual illusions in their works of art. Figure 7.3.3-1 displays a visual illusion where subtle shadows actually mask a potential hill. Just by changing the angle of incident light the depiction changes to one of more contrast. In tile A little contrast is seen, but with the light coming in from the side as in tile B, the hills are now visible.

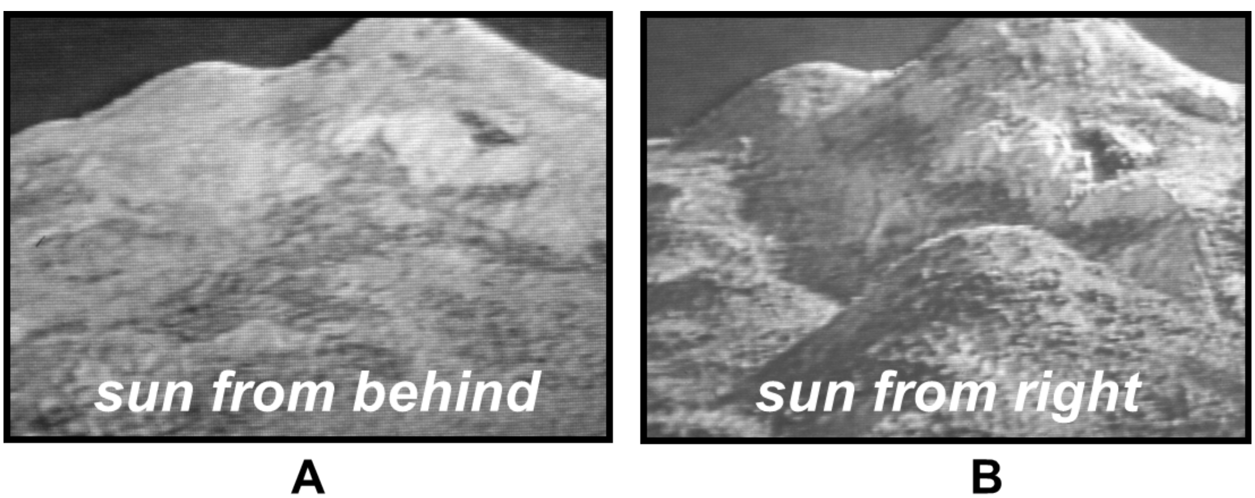

Figure 7.3.3-1. Visual Illusion of a Hill Hidden by the Angle of Incident Light

Such visual illusions abound in the world and create significant problems during flight. Subtle slopes of cloud decks can create an illusion of an aircraft bank; narrow runways may appear longer due to the size constancy illusion, etc. It is important to

note these types of illusions contribute to SD events. Visual ones are not the only ones. We use this type of illusion for the introduction to the world of SD since it is by far the most common. Our mind often struggles to correctly interpret the things we sense, and interpretation can be influenced by our prior experiences and our sensory inadequacies. Some researchers have further defined subcategories of these illusions, but for the sake of simplicity, we'll limit our presentation to the ones that primarily apply to aviation.

7.3.4. Orientation

To get a little closer to the accepted definition of SD, we must define one more term—spatial orientation in aviation. Spatial orientation in the worldly environment is simply the ability of the pilot to correctly perceive the position of an object and the direction in which it lies with respect to a standard coordinate plane—in this case the surface of the Earth. For example, let's consider a parked car. You might recognize characteristic features such as the taillights, bumper, etc. indicating that the vehicle is facing away from you. On the other hand, perception of self-orientation often involves both visual and somatosensory input. The visual system detects the orientation of surrounding objects, which, when combined with experience (memory), presents a constructed representation of the body's orientation with respect to the object's frame of reference. Hence, self-orientation is referenced to other objects in the surrounding environment. The brain also receives proprioception and vestibular cues, which inform the individual if he/she is standing, lying, inverted, etc. However, these cues can be misleading in the complex and dynamic flight environment. With this simplistic and basic concept of spatial orientation, we are now ready to deal with the definition of SD.

7.3.5. Spatial Disorientation

If orientation is about knowing one's relationship to a particular place in space, then SD deals with misperceptions of spatial cues leading to a loss of orientation in that given space. In the aviation environment, self-orientation actually refers to the orientation of the aircraft due to the fact that the pilot and aircraft are coupled. Often, the Earth's surface is used as a stable coordinate reference. However, other objects can be substituted, such as another aircraft, when terrestrial references are unavailable. This is how military pilots orient themselves while flying other than lead in a formation. For a more precise definition, we quote the definition penned by Allen Benson in 1974 when he wrote the following: "Spatial disorientation is a state characterized by an erroneous sense of one's position, motion and/or attitude with respect to the plane of the Earth's surface (or other object)."

Although this definition first remained controversial for many years, it is now accepted throughout the military community as the best definition. It provides a foundation to study the topic and to objectively define the degree of SD being experienced. Essentially, it encompasses all the possible positions, velocities, and accelerations both in translation and rotation for an aircraft within a given Cartesian coordinate system (an orthogonal, three-axis coordinate system) using the Earth's surface as a method of measuring the vertical displacement. It also allows for an understanding of the causes of SD from a sensory perspective.

It is important to note before going further that SD involves not only correct alignment with a standard coordinate system but also spatial location within the geographical boundaries of that three-dimensional (3-D) system. Geographic

disorientation, on the other hand, involves only the misperception of sensory cues (usually visual) in the 2-D sense. When a person loses his or her position while on land, it is often referred to as "being lost." It is a state characterized by an erroneous locational percept but only in the two coordinates that are used to define the surface of the Earth and not the vertical component. This is known as geographic disorientation, and it is analogous to being lost when driving a car.

7.3.6. Vertigo

Vertigo is usually considered a clinical term used to describe a false sense of motion or, in the more classic case, spinning. There are several types of vertigo. This chapter will mention only one—pilot vertigo or pilot's vertigo.

7.3.7. Pilot's Vertigo

Pilot's vertigo is an illusion originally defined as a sensation of rotation occurring during flight. Most flyers refer to all forms of spatial disorientation, with or without subjective rotation, as pilot's vertigo. Pilot's vertigo and SD were for many years considered synonymous. It wasn't until approximately 1990 when the term SD was broadened to include those situations described by pilots as "misorientation" or "unorientation." Getting rid of these terms and developing a commonly held definition of SD helped focus research in the emerging science, which is now known as SD countermeasures. It also permitted critical issues associated with the high workloads in military cockpits to be addressed—the loss of situational awareness. Perhaps most important was physiologic research leading to a comprehensive understanding of human equilibrium and orientation perception.

7.3.8. The Organs of Equilibrium

Three sensory systems are especially important in helping the human maintain his or her equilibrium, orientation, and balance: the visual system, the vestibular system of the inner ear, and the proprioceptive system as shown in Figure 7.3.8-1. Equilibrium and spatial disorientation are normally maintained by the combined functioning of these senses. For most normal physical activities on the ground, these three organs of equilibrium are effective, and the brain interprets their input accurately. However, when man is subjected to the complex motions and forces involved in flight, the organs of equilibrium become less effective in providing meaningful input to the brain. Such errors or misinterpretations are the foundation upon which illusions occur, and in a more global sense, spatial disorientation is often the result.

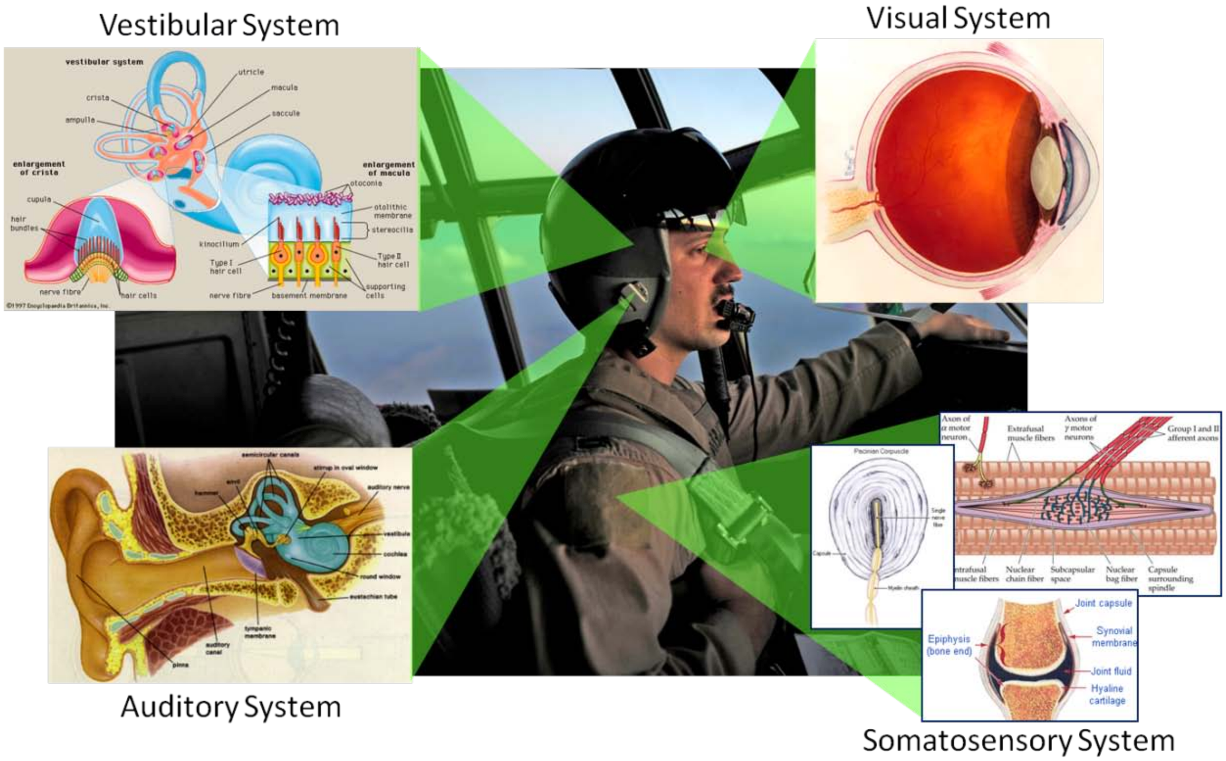

Figure 7.3.8-1. The Integration of the Three Sensory Systems Predominantly Used for Spatial Orientation

Of the three, vision is by far the most important and reliable in flying. The vestibular and the proprioceptive senses are susceptible to producing erroneous or incorrect cues to the pilot due to accelerations varying in both magnitude and direction. However, this was not always common knowledge. It took many years and numerous lives lost to SD to recognize the shortcomings of these two senses in the flight environment. Because the cues from the vestibular and proprioceptive systems can be misleading, it is paramount for pilots to understand the underlying physiology and function. With such knowledge, they are more capable of recognizing errors caused by these systems, thereby leading to fewer incidents.

7.3.9. The Visual System

Vision is the most important of the three senses of orientation. (See section 1.4 for a complete discussion of the principles and problems of vision.) Reliance upon the visual system will be greatly reduced at exceptionally high altitudes, i.e., above 25,000 ft (6,620 m). Without visible exterior structures to provide visual flow cues, velocity and direction of flight become nebulous. Instrument meteorological conditions (IMC), known as being "in the weather," obscure reference points outside the aircraft. These reference points are often used to maintain spatial orientation. When the pilot cannot see these features, the pilot must look inside the cockpit and transition to the flight instruments to maintain awareness of the aircraft's state. These instruments, as mentioned earlier, are the only known countermeasure for SD. Be aware, it is extremely difficult to trust the readings on the instruments when it is already "believed" that the visual information from outside the aircraft is correct. The decision to rely upon

the visual sense and to believe the instruments rather than the input of the other senses demands judgment and practice. The use of flight instruments to maintain spatial orientation requires proficiency and, hence, instrument training.

In flight, the integration of the eyes and the flight instruments is absolutely critical for safe flight. The eyes must constantly scan the instruments for any unexpected changes that might occur because of turbulence, distraction, inattention, mechanical failure—all causes of spatial disorientation. This integration is known to pilots as the "instrument crosscheck."

7.3.10. The Vestibular Apparatus

The inner ear contains the vestibular apparatus, the motion-and-gravity-detecting sense organ. It is located in the temporal bone on each side of the head. Each vestibular apparatus consists of two distinct structures, vestibule proper and the semicircular canals (Fig. 7.3.10-1). Although these organs provide important cues for basic orientation on the ground, they often provide misleading information, or an entire lapse of critical information, during flight. It behooves the pilot to have a basic understanding of how this occurs.

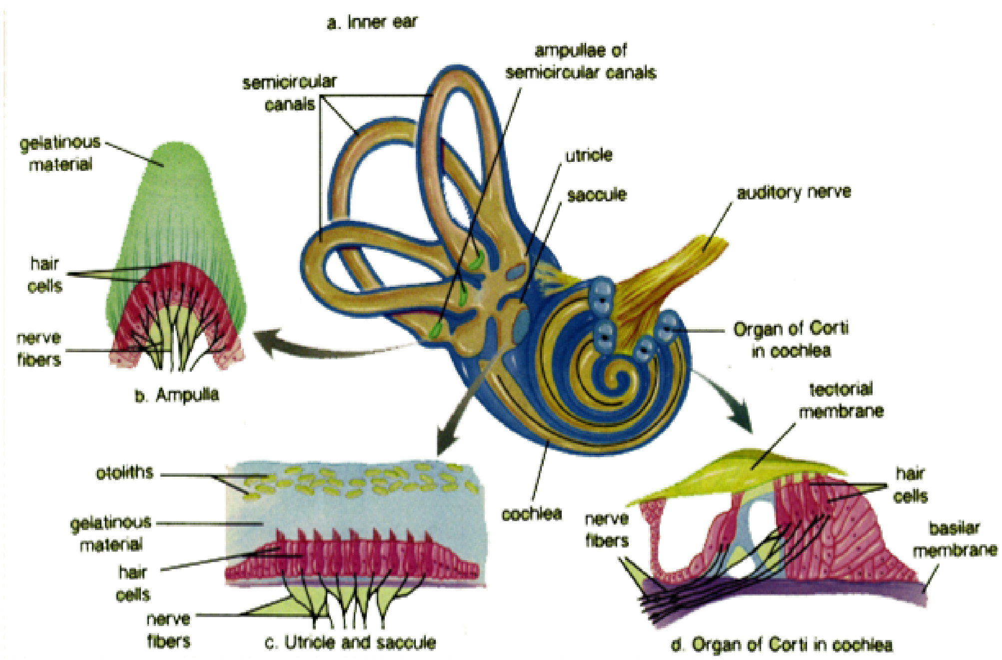

Figure 7.3.10-1. Details of the Inner Ear and the Vestibular System

7.3.11. The Otolith Organs

The otolith organs, the utricle and saccule, are small sacs located in the vestibule. Lining both the bottom of the utricle and the medial wall of the saccule is a patch of cells called a macula. Sensory hairs project from each macula into overlying gelatinous membrane containing chalk-like crystals called otoliths. The otolith organs respond to changes in motion known as accelerations. Changes in head position augment the direction of the acceleration due to the Earth's gravitational pull. This causes the otolithic membrane to shift position on the macula. Because the sensory

hairs in the macula are coupled to this membrane, the shift causes the hairs to bend and send signals to the brain indicating the change in head position. The signal is in the form of the cellular action potential firing rate. When the head is upright in a static environment, the cells are firing at a nominal "resting" frequency. As the macular hairs bend, the firing rate changes to indicate the new situation (see Figure 7.3.11-1). It is this same shearing response that is so predictable on the ground by alerting a person of head position relative to the gravitational vector, yet the same basic mechanism can be very troubling when it happens in flight. Shearing of the otolith in flight is often the result of a net vector containing both the Earth's gravitational pull and the acceleration generated by the motion of the aircraft.

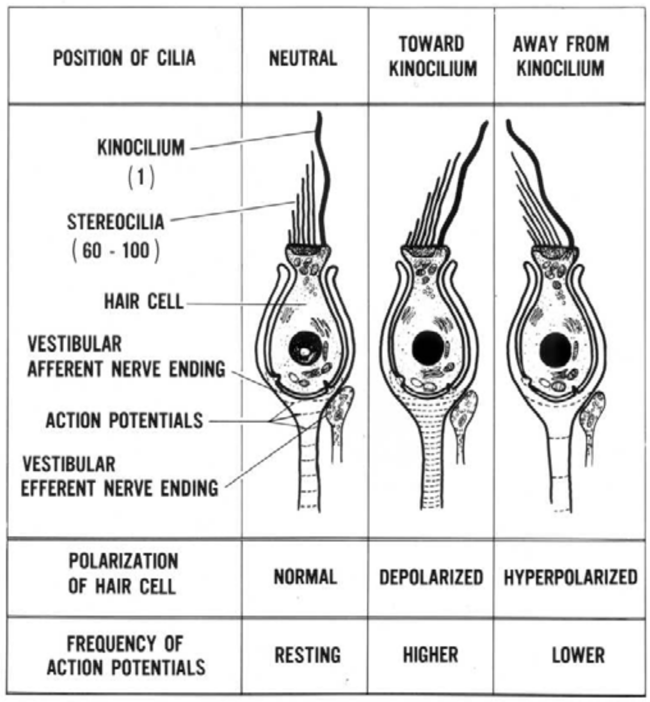

Figure 7.3.11-1. Displacement of the Cilia

Linear accelerations also stimulate the otolith organs, since inertial forces resulting from linear accelerations cannot be distinguished physically from the force of gravity. A forward acceleration, for example, results in backward displacement of the otolithic membranes, which can create an illusion of backward tilt. The misperception is often enhanced if adequate visual references are not available to correct the mental image generated by the vestibular input.

7.3.12. The Semicircular Canals

The semicircular canals, like the otoliths, respond to accelerations. The difference is that the semicircular canals respond primarily to angular accelerations rather than linear accelerations. There are three semicircular canals structured as shown in Figure 7.3.12-1 and are situated in three roughly mutual perpendicular planes. They are filled with a fluid called endolymph, which is put into motion by the inertial torque resulting from angular acceleration in the plane of the canal. Motion of the fluid exerts a force upon a gelatinous structure called the cupula, located in the ampulla of the canal. The translation of the fluid causes hair cells situated beneath the cupula to

bend, thereby stimulating the vestibular nerve. The impulses are transmitted to the brain, where they are interpreted as rotation of the head.

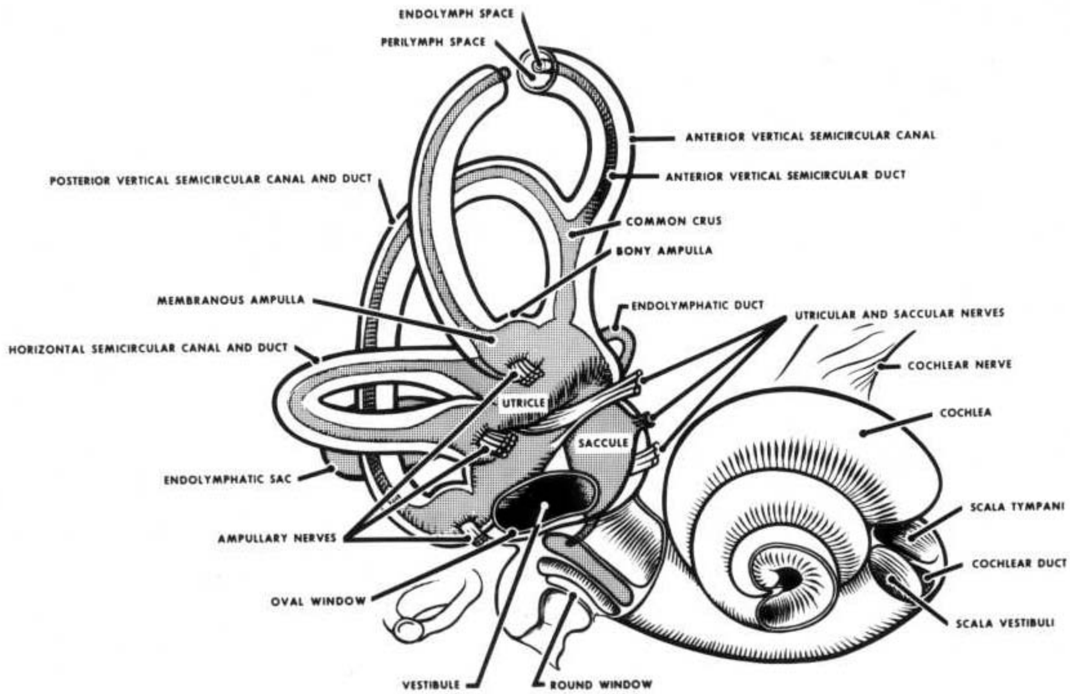

Figure 7.3.12-1. Inner Ear Structure and the Three Semicircular Canals

Since each canal lies in a different plane, they can sense rotation in three dimensions. However, because of gyroscopic physical principles, the resultant signal may produce an unsettling sensation in a dynamic acceleration environment. This interaction can result in a vestibular illusion or, in some cases, a response known as motion sickness. More detail about this “cross coupling” response can be found in the section on motion sickness.

Let’s go through a simple example of how the misperception is generated. When a semicircular canal is put into motion; for example as one rapidly generates angular acceleration to the left, the fluid within the semicircular canal lags behind the accelerated canal walls and bends the hairs in an opposite direction, i.e., to the right. Because the brain has habituated to simple positional changes that occur in a static environment, it tends to interpret the movement of the hairs to the right as angular displacement to the left. If the turn continues at a constant rate for several seconds or longer, the motion of the fluid in the canals catches up with the canal walls and the hairs are no longer bent. The brain receives the completely false impression that turning has stopped although rotation to the left continues. If the visual information is not available to correct the misperception, then the stage is now set for a dramatic and sometimes frightening illusion.

With a sudden stop, the canal walls arrest rotation, although the canal fluid continues to flow for a short period of time due to its inertia forcing the hairs to now bend to the left. This gives the brain a false impression of movement to the right (opposite to the original direction). Given the fact that the illusion can be profound in the absence of other information to correct the misperception, the pilot is naturally driven to counteract the illusion by rotating the aircraft in the original direction—back to the left. Without an instrument crosscheck or visual information to correct the situation, the pilot

would most likely continue the right rotation for a long time. Historically, once this illusion was understood it wasn't long before researchers called the in-flight consequence the "graveyard spin." The first word happened to reflect the usual end point of the SD event.

This demonstration was first discovered in 1927 by Capt Bill Ocker and Capt (Dr.) David Meyers. It remains today as the best demonstration of the inadequacies associated with the vestibular system and SD. There are other systems such as the proprioceptive system that come into play, but the basic understanding remains within this simple demonstration.

7.3.13. The Proprioceptive System

<u>Proprioception</u> includes the vestibular, subcutaneous, and kinesthetic sensors, which enable an individual to determine body position and its movement in space. The subcutaneous pressure receptors and kinesthetic muscle activity sensors are important inputs to the perception of body orientation (Fig. 7.3.13-1).

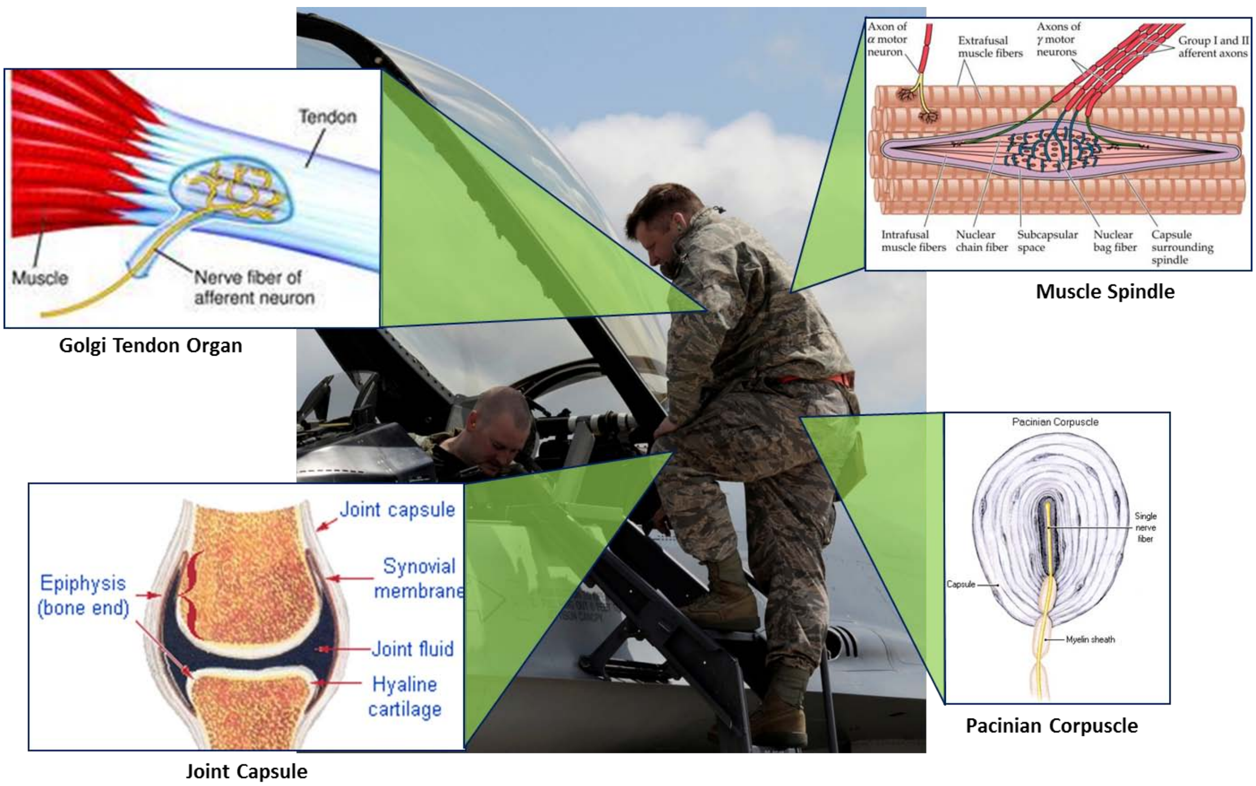

Figure 7.3.13-1. Proprioceptive Receptors Found in Various Parts of the Body

The kinesthetic sense generally does not orient individuals to their surroundings but informs them of the relative motion and relative position of their body parts. These include feedback of muscle stretch, joint position, tendon tension, etc. to the cerebellum. The subcutaneous pressure receptors are capable of informing individuals of their position in relation to the Earth, if they are in contact with some earthbound object. These receptors are stimulated by the pressures created on the buttocks when sitting, on the feet when standing, or on the back when lying down. These sensations provide the "seat-of-the-pants" sense often referred to in flying. While early aviators believed

they could determine their aircraft's position by seat-of-the-pants sensations, they were often fatally mistaken. Inertial forces caused by multiaxis accelerations encountered in the flying environment can cause sensations that have little correlation with the true orientation of the aircraft. For example, rapid linear accelerations may provide a sensation of aircraft pitch up. The bottom line is that the vestibular and proprioceptive cues that provide stable and reliable information on the ground become erratic and misleading in flight. The pilot must learn to suppress these natural cues and trust the instruments displayed in the cockpit.

As you may have surmised, within the broad term of SD, there are two major kinds of illusions--vestibular and visual. Of course nothing is ever definitive, so there are several illusions that result from a mix of both the visual and vestibular sensory responses. The following sections touch upon many, but not all, of the known SD illusions.

7.3.14. Vestibular Illusions

The human vestibular system, which has evolved to work in ground-based environments, is prone to providing the brain with misleading information during flight. This misinformation produces illusionary perceptions. As described previously, the response of the semicircular canals may be inappropriate during angular acceleration prevalent in flight. The otolith organs cannot distinguish between the force of gravity and linear accelerations. Some vestibular illusions are commonly experienced, while the most dangerous are less frequent. These vestibular responses can be further subdivided into illusions related to semicircular canal stimulation and illusions related to otolith organ stimulation.

7.3.14.1 Somatogyral Illusions. Somatogyral illusions are vestibular-induced illusions generated from rotations of the body. These rotations stimulate the semicircular canals due to either angular velocity or angular acceleration, and the result can be one of several well-documented SD illusions.

7.3.14.2 Nystagmus. Angular motion may cause the eyes to pulsate in the direction of rotation in what is known as the vestibular-ocular-reflex (VOR). Nystagmus is the term used to describe a sweeping motion of the eyes in a direction that is opposite of an imposed angular acceleration and followed by a quick return of the eyes to the center position. This occurs with oscillatory repetition of the sweep and return, resulting in an apparent jerking of the eyes in the direction of the angular motion. Nystagmus may appear when rotational eye movement exceeds 3-5 deg/s. And the pilot's head movement on top of the aircraft movement can greatly exacerbate this situation. Natural head movements are of high frequency; however, the visual system, encumbered by relatively slow retinal processing, cannot produce eye movements that stabilize the retinal image. When such eye motion occurs upon cessation of rotary motion, it is called postrotatory nystagmus. Nystagmus can be horizontal or vertical depending on the plane in which the angular acceleration acts and the particular canals stimulated.

7.3.14.3 The Leans. The leans illusion is the most common vestibular illusion derived from stimulation of the semicircular canals. These organs do not perceive rotary motion below a certain threshold. The threshold, under ideal conditions, is described by the product of angular acceleration and the time in which the acceleration

occurs. This product must be equal to, or greater than, approximately 2 deg/s, a constant known as Mulner's Constant. The leans results from unperceived, subthreshold angular acceleration followed by an abrupt and perceptible angular acceleration in the opposite direction. For example, a slow, inadvertent rate of roll may be introduced during flight that is less than the vestibular threshold, thereby making it impossible for the pilot to sense without paying careful attention to his/her instruments. Once the bank error is observed on the attitude indicator, the pilot often initiates a corrective roll in the opposite direction that has an acceleration exceeding the threshold for vestibular stimulation. Because the original roll was not perceived, the pilot feels that he has rolled into a bank in the opposite direction of the original unnoticed roll, even though the instruments indicate straight and level. Pilots in this situation will do one of two things: (1) respond inappropriately to the spatial disorientation by rolling the aircraft in the direction of the original roll, until their vestibular perception indicates the aircraft is straight and level; or (2) trust the attitude indicator and regain control of aircraft attitude, even though they may retain their false vestibular perception of bank. This common illusion is presented in Figure 7.3.14-1.

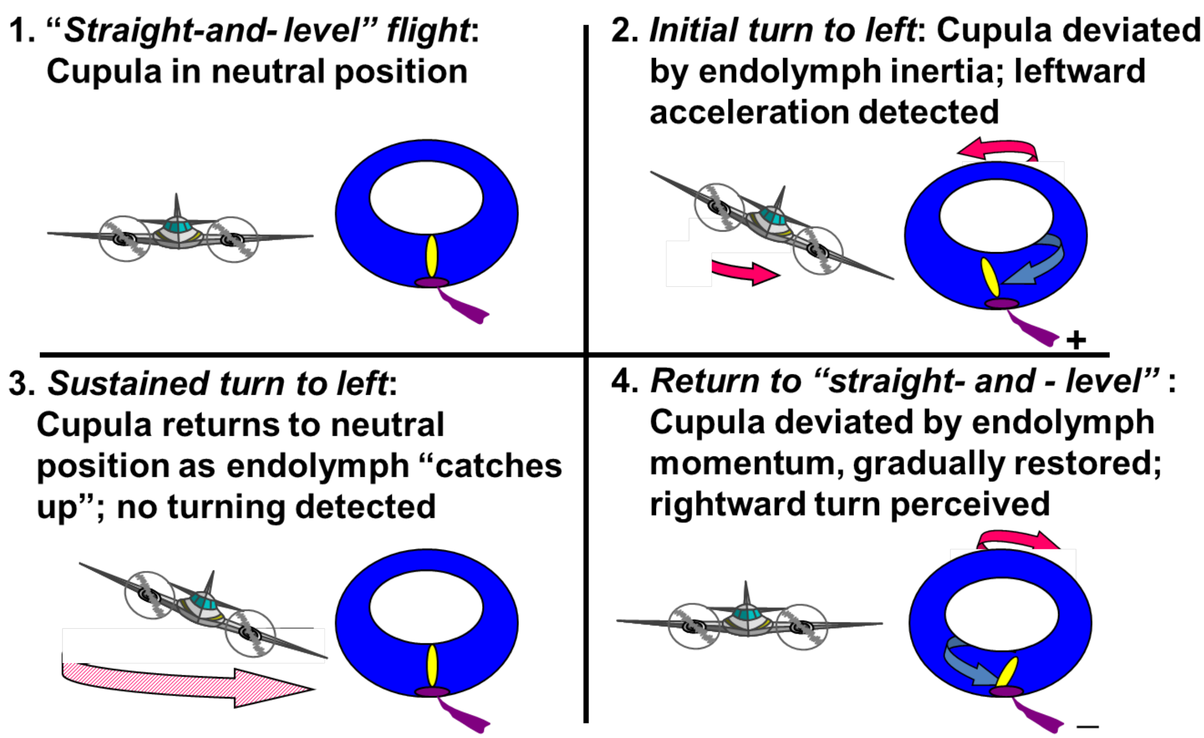

Figure 7.3.14-1. Motion that Could Lead to the "leans"

There is also a visual analogue of the leans illusion. In this case the pilot is responding to the visual information and not necessarily to his or her vestibular signal. Visual leans are most commonly associated with false horizons, such as a sloping cloud deck, sloping terrain, or a shoreline at night. In these situations the pilot tends to orient his or her body and/or aircraft to align with the perceived horizon.

7.3.14.4 Graveyard Spin. The somatogyral vestibular illusion, known as the graveyard spin and described earlier, is appropriately named as it is particularly profound and difficult to eliminate once initiated. The illusion often begins after a pilot

enters and remains in a spin for several seconds. During the sustained spin, the semicircular canals equilibrate to the rotary motion, thereby eliminating the perception of continual motion. As the pilot recovers from the spin, he/she undergoes an angular deceleration that is sensed by the semicircular canals. The central nervous system interprets this sensation as a spin in the opposite direction. Although the pilot's instruments indicate a recovery from the spin, the vestibular system continues to produce a strong sensation of being in a spin that is difficult to ignore. If deprived of external visual references, the pilot is often tempted to make control corrections against the falsely perceived spin. Upon doing this, he or she will reenter a spin in the same direction as the original angular motion. The graveyard spin is illustrated in Figure 7.3.14-2. A proper cross-reference of flight instruments and proficiency in instrument flying will often prevent this situation.

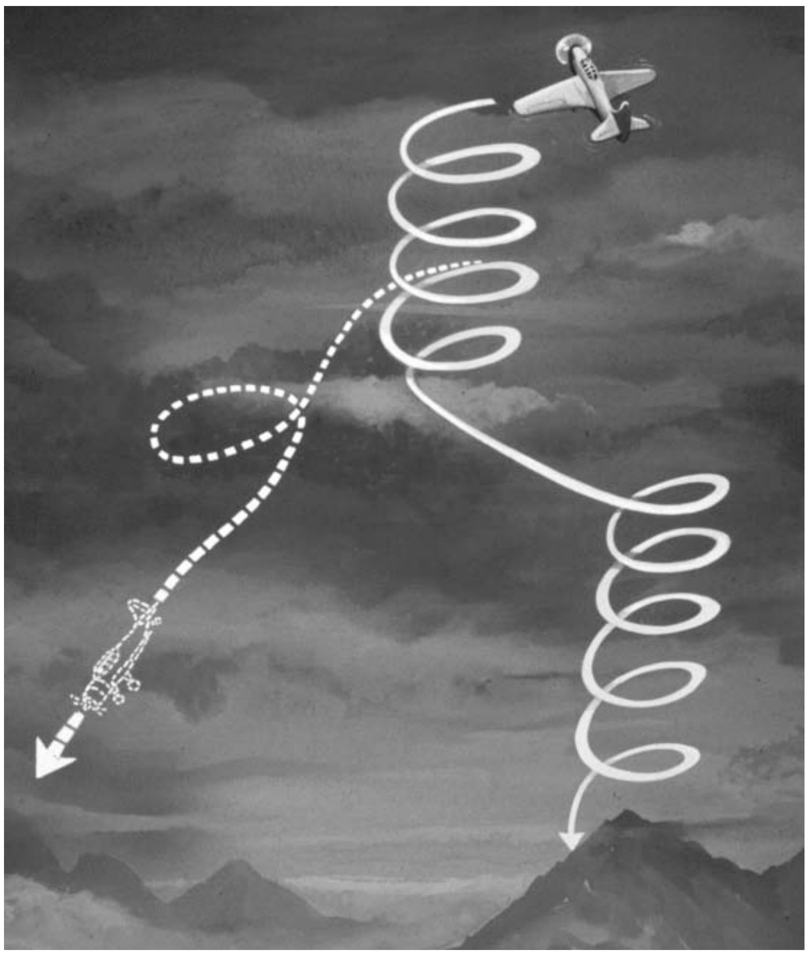

Figure 7.3.14-2. The Real Motion and Perceived Motion (shown by dashes) of the Classic Graveyard Spin

7.3.14.5 Graveyard Spiral. The graveyard spiral may sound like it is very similar to the graveyard spin, but the two are completely different illusions. The former is purely a false sense of rotation (yaw), while the latter is the result of a misperception of the aircraft's bank brought about by a variety of variables, some of which may not be related directly to the vestibular system. Rather than a spin, the illusion is brought about by a slow, prolonged turn (Fig. 7.3.14-3). Even if the pilot senses the initial bank of the aircraft, after a period of several seconds, the pilot loses the sensation of being in

a turn and believes the aircraft to be level. When reestablishing the bank, the pilot places the aircraft in a greater than expected bank and continues a spiraling motion toward the ground. It has been shown that the pilot may easily fail to detect bank even if the bank has reached a magnitude of 90 deg or more. In addition, if not properly trained on an instrument crosscheck, the novice pilot may increase back pressure on the stick to compensate for the loss of lift. However, this kind of stick input has been shown to tighten the descending turn, and the result is a descending corkscrew flight path.

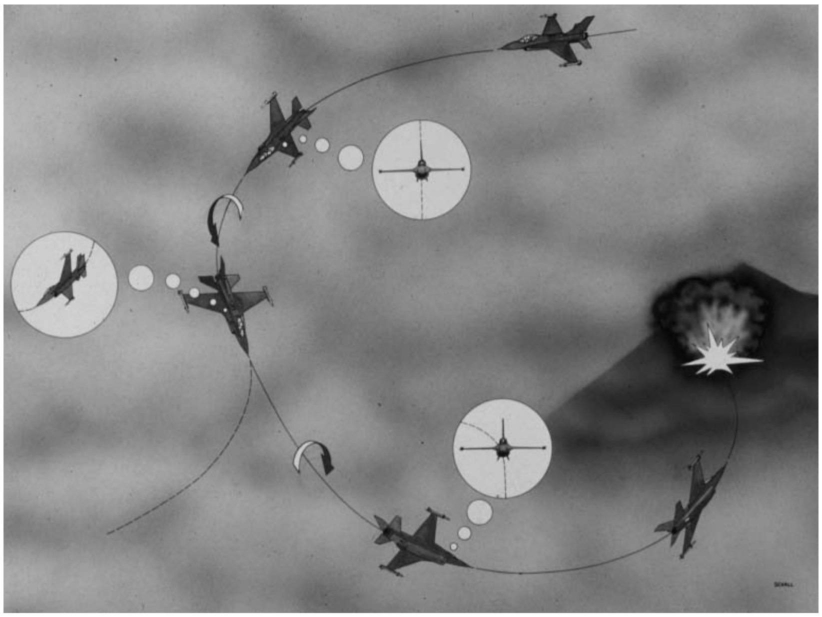

Figure 7.3.14-3. An Illustration of the Actual Path and the Perceived Path of the Graveyard Spiral

The direct cause of the loss of turning sensation remains unknown, although it is likely the result of the habituation of the semicircular canals to the continual turn. Another possibility is that the pilot is sufficiently distracted such that he/she fails to attend to the sensation of turning. Alternatively, the triggering mechanism may result from purely visual illusions such as a slanted cloud bank creating a false horizon (hence a false sense of bank). Regardless, if an inexperienced pilot neglects to crosscheck the attitude indicator and fails to realize the true bank of the aircraft, it is likely that he/she may induce a bank to make the aircraft feel level and begin an unrecognized descent. Should this go unchecked, it can quickly develop into a dangerous condition while the pilot remains unaware of the new spatial orientation of the aircraft. This spiraling descent can result in ground impact, hence the name graveyard spiral, just like its kissing cousin the graveyard spin. An adequate visual crosscheck of the instruments and proficiency in recognizing this SD illusion may likely prevent this situation from deteriorating into such a mishap.

7.3.14.6 Coriolis Illusion. The coriolis illusion (sometimes called cross coupling) is probably the most dangerous of the vestibular illusions because it can be both subtle and overwhelming to the pilot (Fig. 7.3.14-4). It is particularly dangerous at low altitudes and occurs most frequently when a pilot is engaged in a constant-rate turn, such as a penetration turn, holding pattern, or overhead traffic pattern at night. In such

situations, the fluid within the semicircular canals will become stabile and in line with the constant angular rotation (assuming the pilot's head does not turn significantly). Any subsequent quick, large amplitude head movements in any plane other than the turn of the aircraft cause the semicircular canal to be aligned with a different coordinate plane. This causes the pilot to experience the illusion of moving in a plane of rotation in which no real angular motion exists. In attempting to correct the new perceived rotation, the pilot could lose control of his/her aircraft, potentially leading to a serious mishap. However, turns capable of causing coriolis are not common in most fixed wing aircraft and are traditionally more prevalent in rotary wing aircraft or aircraft with vectored thrust.

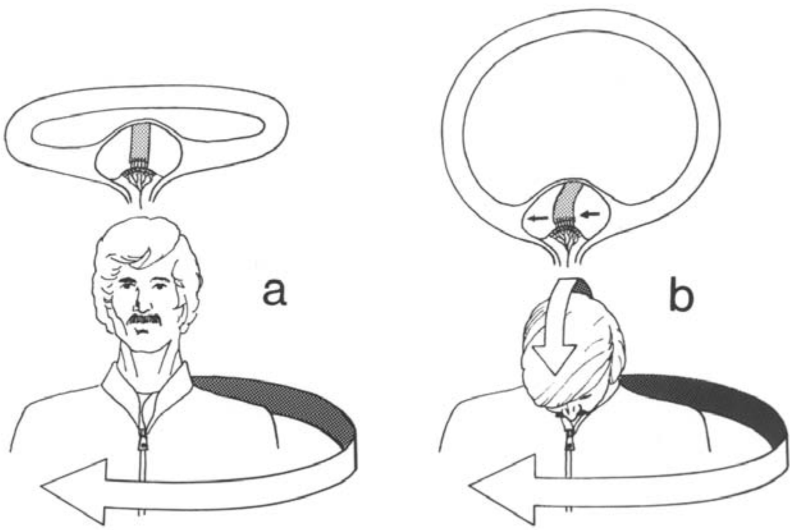

Figure 7.3.14-4. The Motion and Cross Coupling Associated with the Coriolis Illusion

To prevent this illusion from materializing, pilots should avoid sudden, extreme head movements, especially while making turns. To avoid succumbing to the effects of the illusion, pilots should consult their attitude indicators prior to any reflexive "corrective" responses.

It should be noted that the extreme case was explained above, and although this is not common, the more subtle case may always be there. The pilot must beware of conditions leading to coriolis. Even if the sensation is subtle, the end result may be an unnoticed stick input, which could lead to a necessary power and/or pitch adjustment.

7.3.14.7 Oculogyral Illusion. The term "oculogyral illusion" is used to describe the apparent relative motion of an object in an individual's foveal field-of-view while both the person and object are subjected to angular acceleration. Oculogyral illusions can be observed in the cockpit during coriolis stimulation and spins. The oculogyral illusion is caused by semicircular canal stimulation and results in an apparent motion of the instrument panel. The apparent motion may be described as follows.

If a pilot were to stare at an instrument while being rotated to the left, the oculogyral illusion makes the instrument appear to move rapidly to the left. It gradually becomes motionless and then may appear to slowly move to the right, although it may appear motionless with a prolonged constant angular velocity. If the left rotation is

suddenly stopped, the instrument appears to move rapidly toward the right and may not come to rest for 30-40 s.

The direction of the apparent movement of the target is typically in the direction of the angular acceleration in line with the semicircular canals. The magnitude of an oculogyral illusion varies based on the rate of angular acceleration, position of the head, illumination of the target and background, acoustic noise, and the experience of the individual.

In daylight, the apparent motion of a target is seen only after a relatively high rate of angular acceleration. Strong illusions can be initiated with small angular accelerations in the darkness. Therefore, the pilot would be expected to experience the oculogyral illusion as a result of the small angular accelerations experienced while flying at night. Care must be exercised and a constant update of the instrument crosscheck is necessary to prevent this illusion from becoming overwhelming.

7.3.14.8 Somatogravic Illusions. Somatogravic illusions, like their somatogyral counterparts, are generated due to accelerations. However, these illusions are caused by linear accelerations rather than rotational. The otolith organs are stimulated by the net gravitoinertial force, which is the vector summation of linear accelerations due to inertial reactions and gravity itself. For example, with the head upright, the gravitational force of +1G is acting on the gelatinous otolith containing membranes in the utricles and saccules. The resulting pattern of nervous impulses causes the brain to perceive the upright position of the head. If the person is now accelerated such that the *forward* acceleration is +1G, the net force acting on the head (and thus the otolith) is 1.414 G, acting at a 45-deg angle to the vertical. Because the resulting acceleration vector can be produced by a multitude of vector pairs, the source of the shearing force on the otolith can be ambiguous, especially when exterior visual cues are absent and instrument crosschecks have been omitted.

The absolute thresholds of otolith organ function are known, although there is considerable variation among individuals. A change of only 1.5 deg gravitational force vector acting on the otoliths can be perceived under ideal conditions. However, a change in the magnitude of gravitoinertial force of +0.01G has been perceived by experimental subjects. False sensations arise from the stimulation of the otolith organs primarily because these organs are unable to distinguish between the Earth's gravity and superimposed inertial forces resulting from linear accelerations.

7.3.14.9 Oculogravic Illusion. The oculogravic illusion can be described as the apparent movement of an object in the visual field resulting from the linear accelerations placed upon the body. It is thought to result from the inertial response of the eyeball to these forces. The term "oculogravic illusion" has, through erroneous usage, come to mean the false sensation of change of body position that occurs when an inertial force combines with the force of gravity to produce a resultant force. The oculogravic illusion should not be confused with the somatogravic illusion. The former is the result of forces on the eye and the subsequent change in the visual field, while the latter is the result of forces on the vestibular system and the sensations produced from those forces.

7.3.14.10 Pitch-Up or Pitch-Down Illusion. This illusion is synonymous with the somatogravic illusion. However, to keep the generic name of a certain group of illusions different from its parts, this particular illusion is expressed as either a false sense aircraft pitch (up or down, depending upon the net gravitoinertial force). Forward

acceleration without the ability to see external visual cues and an inadequate instrument crosscheck would result in a sensation that the aircraft is pitching up significantly. The intuitive (although wrong) corrective action is to pitch down, which becomes a severe problem during low-visibility takeoffs. It is suspected that a number of pilots have been lost because they experienced the pitch-up illusion shortly after takeoff at night over unlighted terrain or water and on missed approaches. Figure 7.3.14-5 illustrates this phenomenon.

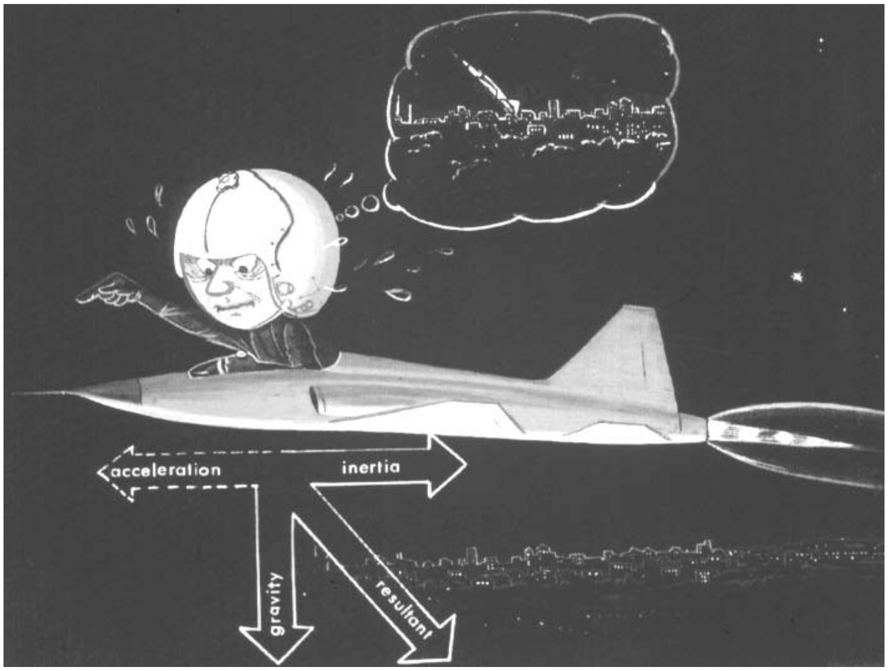

Figure 7.3.14-5. An Illustration of the Pitch-Up Illusion Resulting from Acceleration (the perceived orientation is shown in the bubble)

Furthermore, the illusion of a nose-down attitude occurs during decelerations caused by extending speed brakes or reducing forward velocity such as rapid reduction of the throttles. This is often reported during sudden changes in airspeed during low-level flights.

7.3.14.11 Inversion Illusion. Another variation of the somatogravic illusion is called the inversion illusion. It occurs during an abrupt pushover following a climb. Under these circumstances, the sudden aircraft attitude change and ensuing decrease in gravitational force acting downward on the otolith organs cause a sensation of the aircraft pitching upward. Instinct causes the pilot to try to correct for this illusory attitude by pushing the nose of the aircraft downward, which only intensifies the sensation and the illusion.

7.3.14.12 Elevator Illusion. The elevator illusion is caused by a change in acceleration acting in line with Earth's gravity, which stimulates the otolith organs. The sensation is analogous to the increase in acceleration experienced when riding an elevator from a lower floor to a higher floor. Essentially, the inertial force is detected from below initially, followed by a sudden decrease when arriving at the selected floor. In an aircraft, an upward linear acceleration can occur while the aircraft wings remain level, as in a sudden updraft or a sudden level off. Hence, the pilot will often sense the

resultant force as a climb. If the altimeter is not crosschecked, the pilot is likely to allow the nose to lower while perceiving level flight is being maintained. The opposite occurs when making a sudden level off from a climb. This illusion has been the culprit of several major aircraft accidents.

7.3.15. Visual Illusions and Problems

Humans are visually dominant creatures that rely heavily on visual stimuli to describe the surrounding environment. This reliance on vision has evolved because our vision often provides the most reliable information. This is not meant to imply that other sensory information is unimportant. The other senses often simply support, reinforce, and/or refocus the visual system on stimuli that are of interest. Due to various motions and accelerations along with unique visual perspectives and occasional low-visibility conditions encountered in flight, a pilot cannot be expected to always perceive correctly his or her geographic position, attitude, heading, altitude, and airspeed with natural environmental stimuli. Artificial cues such as the instrument panels within the aircraft have been implemented to assist the pilot to maintain awareness of the aircraft state. Nevertheless, human vision remains prone to perceiving illusions. An additional reason certain visual illusions are more prevalent in flight is due to the increased freedom of motion that allows for visual perceptions that would not normally be experienced on Earth. Some are almost never encountered on Earth (other than with some who have experienced brain damage) because our feet are firmly planted on the ground. We rarely if ever experience a brief absence or reversal of our normal 1 Gz force field. However, fighter pilots can roll their aircraft through 360 deg and experience reversals of the 1 Gz field. In situations where a pilot’s vision is totally focused on a lead aircraft (such as during in-flight refueling), a pilot can easily begin to feel inverted. Reports of such false sensations are commonly discussed among pilots.

7.3.15.1 Confusion Regarding Lights. A common problem associated with night flying is the confusion of ground lights with stars. Many incidents have been recorded where pilots have put their aircraft into very unusual attitudes to keep some ground lights above because they thought the lights were stars. Sometimes pilots have mistaken certain geometric patterns of ground lights, such as freeway lights, with runway and approach lights, or assumed a line of ground lights as the true horizon. Such illusions are illustrated in Figure 7.3.15-1.

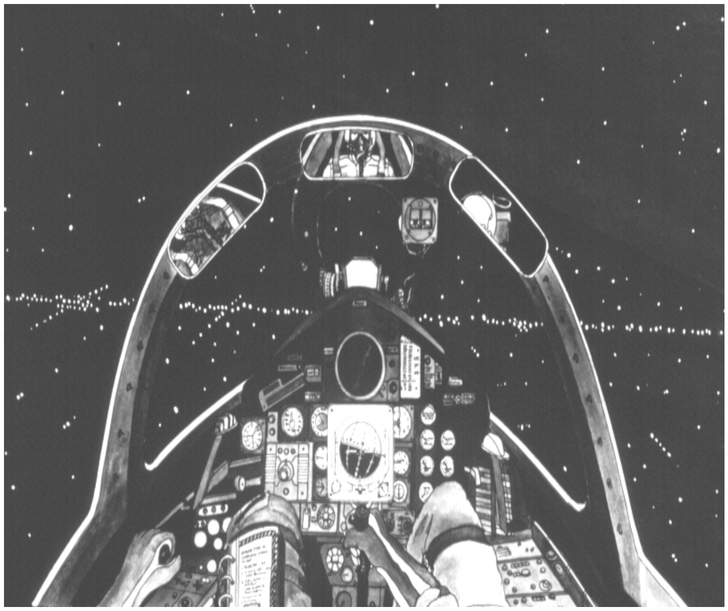

Figure 7.3.15-1. A Blending of the Stars with Ground Lights, Creating a False Horizon

7.3.15.2 False Vertical and Horizontal Cues. As seen in Figure 7.3.15-2, cloud formations may be confused with the horizon or ground. Momentary confusion may result when the individual looks up after prolonged attention to a task in the cockpit. When uniformly sloped, a cloud or horizon line may appear to be level. This will entice the pilot to bank the aircraft to align with the slope while believing the aircraft is perfectly level. Likewise, the false horizon may be experienced at night, even though night flying techniques should place less reliance upon outside references. Isolated ground lights from buildings and other structures may appear as stars. Furthermore, it is possible for ground areas devoid of lights to blend with an overcast sky. As a result, the pilot is susceptible to nosing the aircraft down or completely losing perception of a stable horizon. All perceived horizons must be crosschecked by the aircraft's true reading artificial horizon. When in doubt always choose to follow the artificial horizon unless an instrument malfunction can be confirmed.

Figure 7.3.15-2. An Illustration of a Sloping Cloud Deck

7.3.15.3 Relative Motion or Linear Vection. This illusion is typically caused by peripheral visual cues that are moving relative to the pilot's aircraft. The moving objects can easily be interpreted as self-motion and lead to erroneous aircraft commands to correct the apparent and unanticipated motion. An example of this type of illusion can be found in normal automotive driving conditions. The neighboring automobile creeping forward at a stoplight can give the illusion that one's own vehicle is creeping backwards. And vice-versa is also true. You may misperceive a neighboring vehicle as moving only to find out you were the one actually doing the moving. One may instinctively apply the brakes and be surprised of the sensory feedback. In the flight environment, this illusion is relatively common during formation flying due to the close proximity of the aircraft to one another. Relatively small changes in velocity can produce an intense illusion.

7.3.15.4 Autokinesis. Although not common, the autokinesis illusion manifests only in dark environments (e.g., night) absent of many external cues such as stars and other lights. It begins with a small, singular, and stationary light source within the pilot's field of view. After focusing on the light for 6-12 s, the light appears to move around and can become confusing. Autokinesis usually ceases when the pilot increases his or her visual scan. For this reason, aircraft have several staggered formation lights rather than a single light source. Other factors that will reduce autokinetis are illustrated in Figure 7.3.15-3.

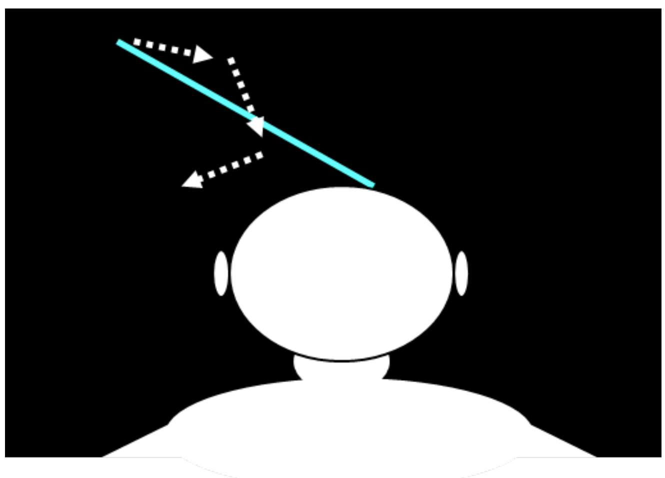

Figure 7.3.15-3. Illustration of a Perceived Moving Light Resulting from the Autokinesis Illusion

7.3.15.5 Glare at High Altitudes. Glare is actually a visual hazard rather than a true visual illusion. Nevertheless, the effect may lead one to experience a more serious SD episode and is mentioned here just to make the reader aware of any cause that may lead to SD. It has been reported that a pilot who flies at high altitudes may encounter the problem of glare from the cloud layer below the aircraft. The facial contour is not formed to protect from glare emanating below the eyes; the sun's reflected rays cause the pilot to develop a visual haziness. The cause of this subjective haze is probably the persistence of a positive afterimage of the bright cloud floor. Other causes, such as fluorescence of the crystalline lens of the eye caused by the greater intensity of ultraviolet light at high altitude and intraocular scattering of light, have been suggested and investigated. The glare from below and the sides, in combination with the lack of light scatter in the environment at high altitudes, may cause a relative shadow on the

instrument panel. Since the external environment is bright and a relatively small amount of light diffuses into the cockpit, the instrument panel may appear to be in a shadow when the pilot turns his/her attention from outside the aircraft to the instruments. The solution to this problem is the use of white light in the instrument panel. The brightness of the panel can then be equalized with environmental lighting using a rheostat-controlled panel light intensity.

7.3.15.6 Haze and Fog. Dust, smoke, and haze caused by water vapor in the atmosphere tend to blur the outlines and reduce the colors and intensities of distant objects. These atmospheric conditions result in apparent increases or decreases in one's perception of distance, depending on the filter and the particular situation. Aerial perspective may play a role in low-level flying, but it does not play a great role in distance judgments during approach and landing. If the atmosphere is excessively hazy or foggy, the pilot often perceives the object to be further away than actual. (Darker things are usually perceived as further away.) Excessive haze or fog would result in the appearance of the runway being farther away than its actual location. When using certain vision-enhancing devices to view the same situation, the pilot's judgment may be just the opposite. Care must be taken when using enhancements to the visual system such as night vision goggles or laser eye protection.

7.3.15.7 Space Myopia or Empty Visual Field. At high altitudes, or during extended overwater flights, pilots may develop physiological myopia due to the normal ciliary muscle tone when the eye is at rest. Under these conditions, one may not have a distant object on which to fixate. In such an empty visual field, a reflex accommodation occurs, creating a varying degree of relative nearsightedness.

Theoretically, individuals with normal vision would be incapable of detecting a target at their normal far point. For example, a pilot with normal visual acuity of 20/20 is able to discern an aircraft having a fuselage diameter of 7 ft (2.1 m) at a distance of 4.5 mi (8.3 km). The same individual acclimated to an empty visual field would not be able to detect the same aircraft at a distance greater than 3 mi (5.6 km).

7.3.15.8 Approach and Runway Problems. Approaches to the runway and landing maneuvers are perhaps the most challenging segments of flight. Hence, when further complicated with compelling illusions, the pilot must be especially vigilant in performing frequent instrument crosschecks to avoid potentially fatal SD consequences. Although there are many visual illusions relevant to approaches and landings, this section focuses on those that are especially common.

7.3.15.9 Night Landing. The reduced visual cues available during night and inclement weather landings can obviously contribute to a loss of situational awareness and provide increased risk of certain SD visual illusions. Specifically, there is always the danger of confusing approach and runway lights, misjudging the approach path, and being unfamiliar with the specific runway and its markings. When a double row of approach lights joins with the boundary lights of the runway, pilots have reported confusion in determining where approach lights terminate and runway lights begin.

The first problem can manifest from the runway lighting coupled with inclement weather. Although it is mandatory to clearly mark the front edge of the runway with runway threshold lights, it is not uncommon for them to be missing. Additionally, approach lighting systems can inadvertently give illusory or false information. When

such situations include dense fog, the result from the decreased brightness can be the illusion of a false climb. Not surprisingly, the pilot is inclined to abruptly pitch down to compensate, which can lead to an impact with the ground or runway.

Most airports have tower-controlled runway lights, while some are controlled by the pilot. That is, the intensity of the runway lighting may be adjusted when the pilot approaches the airfield. If the tower has set the lights too bright, and especially during low-visibility conditions, it will give pilots the illusion that they are closer to the surface than they really are. Likewise, with light intensity that is too dim, pilots may perceive they are further from the surface than is actually the case.

Approach lights have also been known to create a false sensation of bank. This illusion is caused by one row of runway lights being brighter than the other. The brain interprets the brighter row to be closer than the dim row, thereby indicating a bank. Likewise, under certain conditions, approach lights can make the aircraft seem higher when it is in a bank than when its wings are level.

The fact that different airfields utilize different systems certainly complicates the pilot's task of making height and distance judgments during approach and landing. Instrument approach systems, combined with a standardized improved approach lighting and glide-slope system, could eliminate or drastically reduce the false or illusory information received by the pilot. However, such changes are quite costly and therefore and unlikely to be installed. Remember, airfield lighting is not standard and should be reviewed prior to flight into a strange airfield.

7.3.16. Runway Illusions (Day or Night)

Pilot perspective and expected object dimensions can play a major role in the perception of distance to the object and its orientation/slope. Specifically, runways that are narrower or wider than expected can produce compelling illusions of increased/decreased distance from the aircraft. Likewise, varying runway slopes can provide similar illusions of height. Additional detail can be found in the following sections.

7.3.16.1 Width. A runway that is narrower than expected often appears to be further from the pilot's aircraft than actual. Consequently, the pilot may establish a low approach, thereby producing the tendency to undershoot or land short of the runway. Wide runways produce the opposite effect. Therefore, the apparent height is greater than the actual height and often results in a high approach and the tendency to overshoot or land further down the runway.

7.3.16.2 Runway and Terrain Slope. Most runways are level, but those that have some degree of slope can provide deceptive illusions to the pilot. Those with an upslope tend to make pilots feel they are at a greater height above the terrain, causing a normal glide path to seem too steep. Establishing a compensatory glide path that seems more normal could result in an approach and landing that is short of the runway. The slope of the runway should be checked during the pilot's preflight (Fig. 7.3.16-1).

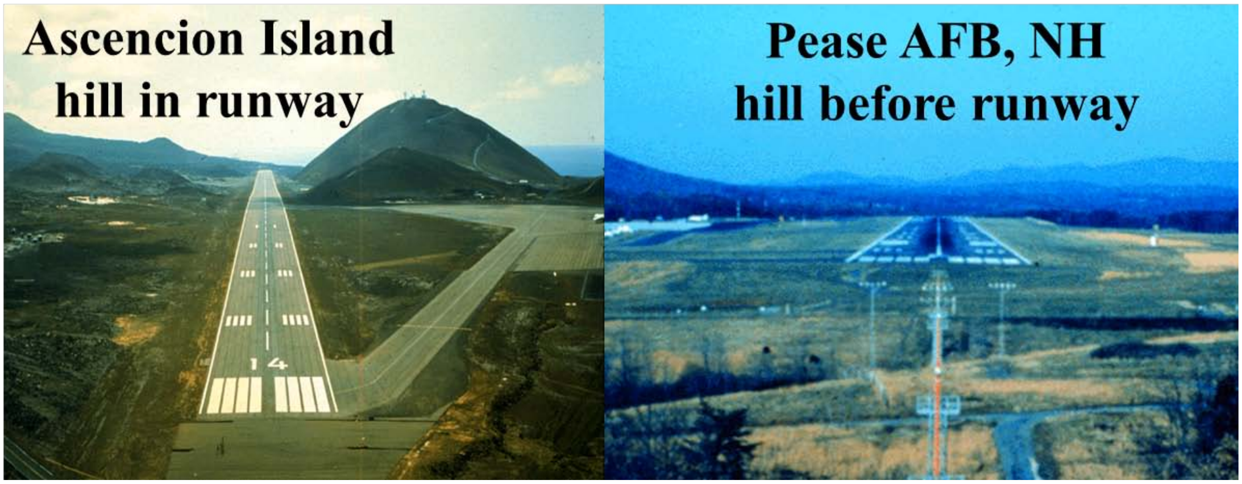

Figure 7.3.16-1. Different Perspectives from Variation in Two Dramatically Different Runways

A similar situation may occur when the runway is level but the approach terrain is sloped downward or below the runway elevation. Such terrain provides an illusion that the aircraft is higher than desired. To compensate, the pilot may fly a revised steeper glide path that will result in collision with the terrain short of the runway. Conversely, an upslope of the approach terrain creates the opposite visual illusory effect (e.g., pilot feels aircraft is too low). Inclement weather and poor ambient luminance generally enhance the effect of these illusions.

When doubts exist concerning the runway and approach terrain slopes, pilots should elect to perform an instrument approach while remaining mindful of the potential runway illusions. Due to the fact that these illusions are often complex (multiple illusions simultaneously), it is advisable to make the first approach and landing into a strange airfield using an instrument-aided approach with visual as a backup when possible (Fig. 7.3.16-2).

Figure 7.3.16-2. Comparison Between a Dimly Lit Runway and a Bright One with the Same Lighting Configuration (the bright lights make you "feel" closer than the darker ones)

7.3.17. Other Landing Problems

Landing over water reduces visual cues to a minimum (e.g., visual flow, peripheral structures), and pilots not accustomed to this environment tend to land either too low or short of the runway. External objects on the approach path serve to provide the information concerning the height of the aircraft. Often, this information is in the form of size constancy. Pilots know the relative size of houses, towers, trees, etc. and can therefore make inferences of height based on the relative size of such objects when peering out the windscreen. Hence, if a pilot was accustomed to landing with an approach over large evergreen or spruce trees and was required to land in the Aleutian Islands, he/she might misjudge height and distance from the runway because the spruce trees in the Aleutians are small and scrubby.

One of the best means of eliminating or reducing aircraft accidents from these types of visual illusory cues is careful briefing of the aircraft crew prior to the flight. A pilot must be aware that distance and height judgments can be affected by biases created from experience and prior knowledge, and he or she should fly an instrument approach if available. If not available, a low approach should be executed before making a landing. The combination of good briefings, aircrew proficiency, and discipline is required for safe approach and landing procedures over all types of terrain and landing field configurations.

<u>Flicker Vertigo</u>. Light flicker is defined as a rapid fluctuation in the brightness of a light source or the appearance that it is being turned on and off repeatedly. When presented to individuals who are sensitive to light strobe effects, the result can be a seizure or disorientation. Typically such "flicker vertigo" occurs when the light fluctuation is low frequency. Other reactions may include nausea, dizziness, headaches, grogginess, and unconsciousness or confusion, uneasiness, nervousness, hypnosis, gastrointestinal discomfort, and a feeling of severe panic. Flicker vertigo is most frequently encountered in rotary wing and single engine propeller aircraft. The spinning

rotors obstruct a light source (such as the sun) each time they pass through an individual's field of view. Hence, if looking up through the rotors, the sun will appear to flicker.

Fatigue and frustration tend to increase the annoying quality of flicker vertigo and make the manifestations more pronounced. Low G-tolerance, hypoxia, hyperventilation, and hypoglycemia seem to suggest a greater susceptibility to the effects of light flicker. Protecting aircrews from the effects of flicker vertigo involves avoidance and reduction of factors that increase susceptibility.

7.3.18. Approach Systems

7.3.18.1 Visual Approach Slope Indicator (VASI). The VASI system consists of a series of four lights designed to give pilots information concerning their glideslope during landing approaches. When all lights are white, the aircraft is high, whereas a change to all red lights indicates the aircraft is low. To inform the pilot that he/she is on the optimal glideslope, the far row of lights remains red while the near row of lights becomes white. By communicating glideslope state information in a simplistic fashion, these lights have reduced the possibility of landing illusions.

7.3.18.2 The Precision Approach Path Indicator (PAPI). The PAPI consists of four light boxes similar to the VASI, except all four are arranged horizontally. Two red and two white lights are an "on glidepath" indication with corresponding color changes the same as the VASI.

7.3.18.3 Fresnel Lens Optical Landing System (FLOLS). This electrooptical landing aid was designed for carrier landings but is also installed at most Naval air stations. The FLOLS appears as two sets of green (datum) lights arranged horizontally on either side of a large yellow light (the meatball). When above the glidepath, the meatball appears above the green datum lights, and the meatball will appear below these lights when low on the glidepath. If more than .75 (3/4) deg from the glidepath, the meatball will disappear. These approach systems are generally helpful, but one must know how they work and not confuse one with the other.

7.3.19. Proprioceptive Problems

The seat-of-the-pants sense is unreliable as an aircraft attitude indicator. Although every pilot is taught this understanding from day one of instrument flight training, many pilots forget the basics and often rely on their seat for orientation information. When coupled with the vestibular signals and a lack of clear visual information, the pilot is ready to experience an SD episode. Hopefully the pilot will recognize the illusion before it progresses too far to recover.

7.3.20. Factors Influencing Spatial Disorientation

A particular set of linear and/or angular accelerations or misleading visual cues will not always produce illusory phenomena. When adequate external visual references are available, spatial disorientation may or may not occur. It is also important to note that the absence of outside visual cues only serves to increase the risk of SD. Therefore, the same complex vestibular cues can be presented to a pilot on several different occasions with the illusory phenomena only being present in a fraction of the trials. Additionally, mental and physical stress and fatigue reduce the pilot's ability to resist SD illusions. As a result, the pilot should always be aware of the potential for SD regardless of the outside visual conditions. Proficiency in instrument or formation flying remains the only proven countermeasure to SD. Additional factors influencing spatial disorientation are included in the following sections.

7.3.21. Cockpit Configuration

Head movements necessary to use some of the cockpit instruments, gauges, switches, and radios during the critical phases of takeoff or approach to landing may cause the coriolis illusion. Aircraft manufacturers are very aware of this problem, and modern aircraft are generally designed to place radios and other related instruments in positions where extreme head movements are not required.

In the past, poor lighting conditions in cockpits have caused difficulty in reading instruments and performing cockpit tasks under normal environmental conditions. Therefore, poor lighting hampered recovery from the symptoms of spatial disorientation. Today, most aircraft have adequate lighting, but all aircrew personnel are not aware of proper lighting techniques. Differences in the intensity of lighting of various instruments and aircraft compartments may cause serious visual problems and compound the symptoms of spatial disorientation.

7.3.22. Visual Flight Rules-Instrument Flight Rules (VFR-IFR) Transition

The experienced, proficient pilot has no difficulty in flying either in visual meteorological conditions (VMC) or instrument meteorological conditions (IMC). When the pilot is making a transition from external visual reference to instruments, or when the pilot is under stress, his or her instrument crosscheck is less than adequate. Consequently, transitioning back and forth repeatedly from IMC to VMC can develop into a dangerous situation with high risk of SD illusions.

7.3.23. Disorientation Produced by Pressure Change in the Middle Ear

A relatively rare form of disorientation can be observed in some aircrew members when flying with upper respiratory infections. These individuals complain of spinning sensations and motion sickness during ascent, descent, or while performing a Valsalva maneuver. The mechanism contributing to this vertigo is not known, although it may be caused by a blocked eustachian tube that suddenly opens. This would allow the rapid dissipation of the pressure differential that develops gradually during assent. The result is a mechanical stimulation of the organs of the inner ear that may produce the sensation of spinning (vertigo).

7.3.24. Stressors

Any factors that adversely affect the judgment or cognitive state of the pilot will decrease his/her chances of survival in a disorientation situation. Physiological stresses such as hypoxia, high G acceleration, and thermal stress can negatively affect the pilot's ability to prevent or recover from a spatial disorientation event. Similarly, self-imposed stresses, such as alcohol and certain medications, will predispose a crewmember to spatial disorientation and make SD incidents more severe and the successful recovery from SD less likely.

Psychological problems and stresses also predispose a crewmember to disorientation. One such condition is fascination or target fixation, which results when a pilot ignores orientation cues while his/her attention is focused on some other object or task. A missed radio call is often considered a sign of fascination or attention narrowing. This is often called task saturation. Although all factors contributing to fascination are not well documented, it is generally accepted that hypoxia, fatigue, drugs, and basic personality are usually influential factors.

7.3.25. Conditions Most Conducive to Spatial Disorientation

A few of the conditions most conducive to SD are listed. A complete list is beyond the scope of this chapter.

- weather
- lack of visual references
- poor instrument crosscheck
- loss of situational awareness
- distraction
- personality
- health

7.3.26. Incidence of Spatial Disorientation

It has been repeatedly observed that spatial disorientation is now experienced by almost all pilots on many sorties. This was not always the case. Until recently most pilots would not admit to experiencing SD. The cause is most likely due to a poor understanding of the causes of SD. Perhaps an increased knowledge base of SD definitions and causes has led to greater recognition of SD events. Nevertheless, unrecognized SD will, of course, remain unreported, thereby skewing the results and providing only a portion of the true number of SD events. The danger presented by SD is evidenced in the significant number of disorientation accidents resulting in fatalities.

Fighters and jet trainers accounted for 84% of the spatial disorientation accidents; however, such accidents were also found to occur in multicrew bombers, cargo-utility aircraft, and helicopters. Nineteen percent of disorientation accidents occurred during the takeoff departure phase of flight, 18% during the approach-landing phase, and 63% during the in-flight phase. The majority of accidents occurring in-flight involved formation flight, aerial refueling, gunnery, or aerobatic maneuvers.

These statistics do not include undetermined accidents, a category that involves approximately 10% to 12% of the total annual number of Air Force aircraft accidents. It is possible, based on the phase of flight or type of fight activity, that a number of these

accidents were caused by, or related to, SD. The large numbers of accidents coupled with a significant loss of life and aircraft necessitates a concentrated and continuing program of prevention and training. To be effective, such training must include academic presentations, ground level simulations, and in-flight training.

7.3.27. Preventing Spatial Disorientation

Training, experience, and professional knowledge are the keys to preventing accidents caused by spatial disorientation. There are only two accepted countermeasures for SD—awareness of it and a good instrument crosscheck. This chapter provides the reader with a beginning to awareness. It is important to develop a habit of continual SD education and refresher training throughout the lifetime of the pilot. The pilot must constantly practice his or her instrument crosscheck during flight training. The following sections examine these objectives in more detail.

7.3.28. Training

Indoctrination of pilots is the first important step to take in the fight against spatial disorientation accidents. Lectures, demonstrations, and movies discussing sensory functions and the conditions in which they become inadequate must be given to pilots by physiological training officers and flight surgeons. Updating and improvement of training aids should be accomplished frequently to ensure adequate dissemination of pertinent knowledge to the pilot population. Summaries of accidents, statistics, and trends should be used in such training programs.

7.3.29. Experience

While experience alone, as measured in terms of flying hours, does not preclude occurrence of spatial disorientation, several experience factors are involved. Experience gained in ground-level simulations using the Barany chair, new SD training devices like modified flight simulators, and basic flight simulators themselves, if used properly, will reinforce the fact that sensory illusions are a definite threat to the pilot's ability to maintain orientation. Ideally, ground trainers would allow the pilot to fly the simulator into an environment that produces an illusion or disorientation. Next he/she would be required to recover using instruments that display actual orientation. Such a trainer would reinforce the reliance on visual input from the instruments and prove that disorientation can be corrected. However, such simulations are not available, and the technology to do such activities is only recently being developed.

Presently, experience with SD illusions while at the flight controls is obtained only in-flight. Experience in actual instrument flying and the proficiency gained contribute to prevention of spatial disorientation accidents. However, it is important to note that maintaining minimum currency requirements for instrument flying may not be sufficient since all IFR-rated pilots involved in spatial disorientation accidents can be presumed to have met these requirements. The difference between the mandated "currency" and being "proficient" can often be of great consequence.

7.3.30. Knowledge

Cumulative knowledge gained from studies of spatial disorientation accident trends has resulted in alterations to the art and science of flying. Aerospace manufacturers are now aware of cockpit configuration issues, instrument design, and instrument placement. These critical design corrections have consistently contributed to the reduction of SD accidents.

Both basic and applied research in vestibular physiology and illusions continues to provide knowledge that will reduce the risk of SD. Aircraft accident investigation teams must compile data relative to runway conditions, width, length, lighting slope and surrounding terrain, and human factors that can reveal factors responsible for certain types of accidents—all relevant to illusions or disorientation.

7.3.31. Overcoming Spatial Disorientation

While prevention of SD is of prime importance, recommendations regarding actions a pilot should take if he/she becomes disoriented must be included in any discussion of spatial disorientation. The following sections describe standard recommendations for overcoming disorientation.

7.3.31.1 Get on the Instruments. The visual input from the instruments is fundamental to the recovery from the effects of spatial disorientation. Do not transition back and forth between instruments and visual references. Establish and maintain a good instrument crosscheck.

7.3.31.2 Believe the Instrument Indications. The pilot must learn to ignore, overcome, or control the urge to believe false sensations perceived from the supporting body senses. Concentrate on the instruments to shorten the effects of the symptoms of spatial disorientation.

7.3.31.3 Place the Head Back into the Headrest. Minimizing head movements and establishing a constant head position with respect to the neck will tend to minimize effects of SD.

7.3.31.4 Fly Straight and Level. Once the pilot attains straight and level flight from information provided by the instruments, he/she should avoid further maneuvers until full orientation is attained and sensory illusions are minimized.

7.3.32. Turn the Controls Over to the Other Pilot in Multipiloted Aircraft

After turning over the controls, the pilot must get on instruments to regain orientation and resist the tendency to resume or take control until full orientation is attained. If the aircraft is equipped with an auto-pilot, it should be utilized.

<u>Egress</u>. If the pilot cannot achieve orientation, particularly in situations involving low altitude, ejection may be the only chance for survival. In high-performance aircraft, the decision to eject must be made quickly. Pilots must know before flight what their course of action will be under such critical situations.

7.3.33. Summary

Man possesses unique physiological systems that provide information pertaining to orientation, body position, and motion. Visual, vestibular, and proprioceptive systems are influenced by flight maneuvers and can produce motion sickness and spatial disorientation. The severity of sensory illusions depends in part on how the pilot decides to utilize sensory information to control the aircraft. A correct decision results in adequate control of the aircraft, but an incorrect decision may prove fatal. Reduction in external visual cueing caused by low ambient light or inclement weather and physiological, emotional, or self-imposed stresses will greatly enhance a pilot's susceptibility to illusions. Special training and instrument flying proficiency are paramount to ensuring safe flying and recovery from SD.

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Concept

Spatial disorientation

Vocabulary

Flicker vertigo
Illusion
Orientation
Otolith organs
Proprioceptive system
Semicircular canals
Vertigo
Vestibular illusions

7.4. Motion Sickness

Lee Diekmann, MSgt (ret) and Capt Quentin Bagby, USAF, BSC

7.4.1. Prevalence of Motion Sickness During Flight

Motion sickness has been well known for thousands of years. Ancient seafaring nations were very familiar with this malady. In fact, the term "nausea" is derived from the Greek word *naus* (ship). Motion sickness has become increasingly prevalent with development of the many forms of vehicular travel, amusement park rides, and ever more dizzying visual stimuli. Various names give an indication of this ailment's many causes: seasickness, airsickness, car sickness, amusement-park-ride sickness, motion-picture sickness, microscope sickness, flight-simulator sickness, and space-motion sickness. Surveys have found that car sickness occurs in 58% of children, space-motion sickness occurs in 50% of shuttle astronauts, and incapacitating airsickness occurs in 29% of airline pilots. Up to 100% of ship passengers become seasick under rough conditions.

It has been reported that 11%-39% of military student pilots experience motion sickness, but after implementing an airsickness management (ASM) program, only a 1% washout rate has been noted (Dobie, 1974; Hemmingway & Green, 1945; Tucker et al., 1965). Once a student has overcome motion sickness, it is rare for the symptoms to return, at least to the extremes found before starting the program.

7.4.2. Physiological and Psychological Causes of Motion Sickness

One of the most accepted physiological causes of motion sickness is thought to be a mismatch between sensation and expectation or a mismatch between different sensory channels (Rubin, 1942; Graybiel, 1969; Ernsting et al., 1999). In humans, movement through the environment is inferred by two principal sensory systems: the visual sense and the two components of the vestibular system of the inner ear. The vestibular system includes the semicircular canals, which detect angular acceleration, and the otolith organs, which sense linear acceleration (other proprioceptive sensations have a minor contribution to motion sickness). Earlier theories that motion sickness is produced by vestibular overstimulation have been discounted. It is now fairly widely accepted that motion sickness is caused by conflicting inputs between the visual and vestibular systems (vestibular mismatch) or between the two vestibular systems and comparison of those inputs with the individual's expectations derived from previous experience.

The conflicting sensory impressions can occur due to purely visual stimuli as well as via vestibular involvement. Another potential evolutionary relationship between vestibular disturbances and an emetic response may be in the effect of poisons on the vestibular system (Money & Cheung,1983). Jackson (1994) proposed a multimodal conceptual model of airsickness onset involving behavior, affect, sensation, imagery, cognition, interpersonal, and drugs/biology.

Anxiety may be linked to a higher incidence of airsickness (Tucker & Reinhardt, 1967; Ryback et al., 1970) and may be related to motivation factors. In a presentation of a neural mismatch model of motion sickness, Reason & Brand (1975) and Reason (1978) cite a description of sensory rearrangement (Reason, 1970). The eventual

reduction in symptoms can take place without any change in the stimulus that caused the symptoms.

A neural mismatch can also cause simulator sickness (O’Hare & Roscoe, 1990). Depending on cues from visual or vestibular systems and how they fail to match results in different types of motion sickness as described by Benson (1978, 1984).

7.4.3. Symptoms and Susceptibility of Motion (Air) Sickness

Characteristically, motion sickness begins with epigastric discomfort often described as "stomach awareness," which is usually accompanied by increased salivation, belching, and a feeling of bodily warmth. With sustained exposure to the triggering stimulus, symptoms progress to nausea, pallor, sweating, and, eventually, vomiting. Some researchers suggest that there is another, distinct syndrome of motion sickness that lacks these gastrointestinal complaints and is instead characterized by drowsiness, headache, apathy, depression, and generalized discomfort. It is quite likely that many people experience both syndromes to varying degrees.

Changes in behavior and performance are decreased spontaneity, inactivity, or being quiet or subdued; decreased muscular coordination and eye-hand coordination; decreased squeezing force in the hand; decreased ability to estimate time; and decreased performance of arithmetic computation.

The cause of motion sickness is generally considered to be a mismatch of vestibular and visual sensations. However, actual movement of the body is not necessary to produce symptoms. Purely visual stimuli, such as those from flight simulators, video games, panoramic movies, or even the movement of slides under a microscope, can produce symptoms more effectively than actual physical motion. The degree of motion sickness appears to be directly related to how well the visual stimulus simulates motion. Approximately 15% of individuals suffering from motion sickness in the flight environment experience this type of sensory conflict.

Not everyone is susceptible to motion sickness. Children younger than 2 yr of age are rarely affected, but susceptibility rapidly increases with age, peaking between 4 and 10 yr and then gradually declining. Recent ingestion of food, particularly dairy products and foods high in sodium, protein, or calories, has been associated with increased susceptibility. Anxiety and preexposure tendency correlate with subsequent motion sickness. In the flight environment, it is estimated that 85% of motion sickness cases result from psychological stress.

7.4.4. Treatment Methodologies

Treatment methodologies are tailored to the specific type of mismatch, e.g., acclimation training reduces the mismatch between sensation and expectation. Acclimation implies adaptation, which has been described (Benson, 1984) as an essential feature of motion sickness treatment.

7.4.5. Nonpharmacologic Therapy

Alternative medicine remedies are becoming increasingly popular, and many have been recommended for treatment of motion sickness. The most popular herbal preparation for nausea is ginger root given in candied form, powdered in capsules, or as a tea. Although there is much anecdotal evidence that ginger is beneficial, a controlled

trial found no anti-motion sickness activity. However, many post-ASM graduates have provided testimony to the benefits of taking ginger as a dietary supplement. At most flight training bases, ginger snaps are in high demand.

Acupressure has generated a great deal of interest as a nonpharmacologic means of preventing motion sickness. One study involving the popular acupressure wristband found no evidence that the band prevented motion sickness, compared with a placebo. Insufficient stimulation was cited as a possible reason for failure. A subsequent trial found that continuous vigorous manual stimulation was required to achieve a significant benefit. Acupressure has thus been deemed impractical in the flying environment.

7.4.6. Pharmacological Therapy

The preferred medication to suppress motion sickness symptoms is a combination of dextroamphetamine sulfate (5 mg) and scopolamine HBr (0.5 mg) tablets or patches (Scop/Dex). Scopolamine is the anti-motion sickness medication but requires a stimulant to combat its depressive effects. This pharmacological combination should be ingested 2 hr before flight. Synergistic effects provide the user with a feeling of being invincible and in control, which is advantageous in overcoming extreme symptoms of motion sickness by building both physical and psychological confidence.

7.4.7. Alternative Therapy

Alternative therapies have been thoroughly researched and time tested to prove their reliability. These include rest, hydration, diet, physical fitness, biofeedback training, progressive relaxation training, diaphragmatic breathing, and motion acclimation therapy using the Barany chair.

Other therapies include precautionary instruction to (a) ensure seat height is adequate to provide sufficient visual cues to minimize mismatch between visual and vestibular cues, (b) ensure adequate hydration, (c) maximize airflow to head area, (d) minimize restrictive clothing, (e) emphasize controlling rate and depth of breathing (Fleur et al., 2003), (f) actively fly the aircraft versus being a passenger, (g) replace negative thoughts of motion sickness with task-oriented thoughts like “crosscheck,” and (h) discuss interpersonal factors to include changing instructor pilot (IP).

7.4.8. Airsickness Management Program

Motion sickness programs have in years past been primarily used during Joint Specialized Undergraduate Flight Training (JSUFT). More recently, others have been using variations of the time-tested program to address motion sickness issues in other crew positions. Human Performance Training Teams (HPTT) have been using the training profiles to assist helicopter door gunners, AWACS mission crew, and high altitude airdrop mission support personnel overcome debilitating airsickness.

Undergraduate Pilot Training programs (Giles & Lockridge, 1985) have been quite successful. These seat-of-the-pants programs are more similar than different in that their procedures closely match, but their philosophy sometimes differs. As of this writing, there is an ASM guide (Air Education and Training Command (AETC) Draft Instruction) that, when finalized, should minimize differences. When the draft AETC instruction (AETCI) becomes official, all units will have standardized programs.

AETCI 48-102, *Medical Management of Undergraduate Flying Training Students*, includes a description in very broad terms of a four-phase ASM program. The four-phase program as listed in AETCI 48-102 is summarized below.

Phase 0. Phase 0 constitutes an initial introduction to ASM. Prior to any flying, all individuals are given a briefing and literature by Flight Medicine or Aerospace Physiology personnel on the prevention of airsickness. This may include education of causes, symptoms, and prevention of airsickness in the flight environment; stress management; progressive relaxation; diaphragmatic breathing; and nutrition guidance.

Phase I. Individuals experiencing their first episode of airsickness will report to Flight Medicine before their next flight to rule out possible underlying medical issues. Flight Medicine will review the airsickness episode with the individual to determine if preventative measures and techniques outlined during Phase 0 were applied both before and during flight. If no medical condition is found, the individual should be returned to flight status.

Phase II. Treatment for the second episode of airsickness is identical to Phase I; however, it also involves the flying squadron, Life Skills, and Aerospace Physiology personnel. Flight Medicine has the option of treating with Scop/Dex in accordance with AFI 48-123, AETCI 48-102, and AETCI 36-2205. Medications are taken 2 hr before flight. Treatment will be limited to a maximum of three consecutive sorties during training. JSUFT students will stop pharmacological treatment no later than five sorties prior to initial solo.

Flight Medicine will establish communication with flight commanders or supervisors to ensure awareness of airsickness problems and allow tracking of the individual's progression.

The individual also receives a mandatory referral to Life Skills to evaluate for manifestation of apprehension, review stress management and progressive relaxation techniques, and conduct biofeedback training (if available). Following Life Skills, the individual will report to Aerospace Physiology to be interviewed by an ASM instructor. This interview is very important because it allows the instructor to thoroughly explain alternative therapies and how they work to counteract airsickness symptoms. The majority of airsickness cases can be alleviated through alternative therapies; therefore, emphasis should be placed on these techniques during the interview.

Phase III. Individuals experiencing a third episode of airsickness will report to Flight Medicine for medical evaluation. Flight Medicine has the option of treating with Scop/Dex following the same guidance listed under Phase II. The principle behind Scop/Dex is to prevent an aversion to flying based solely on airsickness. Generally, Scop/Dex will not be prescribed for less than three episodes of airsickness or in combination with Barany chair training. It will also not be prescribed for JSUFT students within five flights of either a check ride or solo flight. If, after three consecutive sorties on Scop/Dex, the individual experiences airsickness, he/she will be enrolled in motion acclimation training at Aerospace Physiology. Following the second and third airsickness episodes, Flight Medicine has the option to either use Scop/Dex or enroll the individual in motion acclimation training.

7.4.8.1 Acclimation Training. Acclimation training is usually conducted by Aerospace Physiology personnel over the course of three consecutive days, using the Barany chair as the chief training device. Each day of training or session includes two or three each 10-min "spins." The ultimate goal of these training spins is to allow the students to practice using the techniques taught to reduce their nausea in a safe (outside the flying) environment. It is not meant to evoke vomiting, as that would be counterproductive. The instructor must be aware of the student arousal level and capabilities at all times to avoid causing the student to vomit.

7.4.8.2 Diet. The importance of a good diet cannot be stressed enough, not only for physiological reasons, but it has been suggested that utilizing the correct diet will also reduce stomach awareness during flight. It must be emphasized that an empty stomach will not eliminate airsickness symptoms and is counterproductive. Students should eat something prior to flight but minimize or eliminate dairy products and greasy, acidic, and high fat content foods that require increased stomach acids to digest. Foods containing complex carbohydrates appear to work best (Lindseth & Lindseth,1995). Students should alter their preflight diet to reduce fats and salt as much as possible and moderate their total intake to reduce stomach awareness during flight.

7.4.8.3 Head Movements and Visual Field. Minimizing excessive head movements will reduce cross coupling in the vestibular system. When semicircular canals are stimulated in a particular plane of rotation, head movements can disrupt this motion and/or introduce a new rotation, creating cross coupling. Ensuring the visual field has minimal obstructions will help reduce the effects of this cross coupling (Shupak & Gordon, 2006).

7.4.8.4 Biofeedback. Some motion sickness programs have the added capability of using biofeedback (Levy, 1981; Dobie & May, 1994). This training is usually used after all other avenues listed above have been tried and the student is still experiencing debilitating motion sickness. But, it can be helpful at any time in the program if the flight surgeon recommends it. There is no set number of biofeedback training sessions required. The sessions needed are determined on a case-by-case basis. No set Air Force wide profile has been issued; however, experience shows that helping students concentrate on rhythmic/relaxation breathing and muscle relaxation will help them to lower their arousal level. To gain the students' confidence, the session may show the students how breathing can be entrained with heart rate variability, giving them the idea that they can execute a physiological change in their body, something they might not have had any idea they could accomplish. Another physiological indication would be an increase in skin temperature, which can be related to a progressive state of relaxation. Depending upon where the electromyogram sensors have been placed, the instructor can show the student any progressive relaxation that has taken place during the training session. Profile for subsequent sessions can concentrate on tensing and relaxing muscle groups to simulate the stresses of flying and learning new flight maneuvers.

7.4.8.5 Cognitive Behavior Therapy. As evaluated by Cowings & Toscano (1982), autogenic-feedback training appeared to be a successful training tool in overcoming airsickness. Jackson (1994) proposed a multimodal conceptual model of airsickness treatment involving behavior, affect, sensation, imagery, cognition, interpersonal, and drugs/biology.

7.4.8.6 Other Remedies. Over-the-counter drugs and herbal remedies should be cleared through Flight Medicine. Mechanical devices such as acupressure bands are usually associated with psychological effects and should be approved through Flight Safety.

7.4.8.7 Refresher Spin. Spinning is employed at some pilot training bases, and may have different names associated with it. Refresher Spinning is different from the 3-day airsickness training in that it is only warranted after the initial 3-day program has been exhausted. The instructor will try to acclimate the student to the specific aircraft maneuvers that have been causing the airsickness. The instructor conducts an interview to nail down these specific aircraft maneuvers and recreate their vestibular sensation in the Barany chair. This helps students employ all previously taught techniques during a close simulation of the aircraft maneuvers that have been plaguing them. Traditional Refresher Training is one spin session to reacclimate a motion-sickness-susceptible individual after a break in flying.

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AETC Draft Instruction. Airsickness Management (ASM) Guide. December 2005

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Concepts

Airsickness management (ASM) program
Motion sickness

Vocabulary

Barany chair
Neural mismatch
Simulator sickness
Vestibular mismatch

7.5. Impact and Ejection

John R. Buhrman, James W. Brinkley, and Jennifer L. Davis

7.5.1. Introduction

Impact acceleration is experienced in everyday life as a result of slips and falls, industrial accidents, and automotive crashes. In the Air Force these events also occur, but the most relevant exposures to impact accelerations are aircraft crashes and the multiple short-duration impact acceleration exposures experienced during an emergency escape from disabled aircraft.

It is important to consider a few fundamental definitions to more fully understand this subject. Acceleration is defined as a change in the magnitude and/or direction of the velocity of a body. The term "deceleration" simply means an acceleration that reduces an established velocity of a body. The dimension of velocity is ft/s (or m/s) and acceleration is ft/s^2 (or m/s^2). An object dropped in a vacuum at the Earth's surface will accelerate at 1 g. The value of g is 32.17 ft/s^2 (9.807 m/s^2) by international agreement. Acceleration is often expressed in terms of multiples of the acceleration caused by the force of gravity. For example, an acceleration of 322 ft/s^2 is equal to 10 g. Confusion results from referring to "g" as a unit of force instead of acceleration.

In aviation, pilots, physiologists, and others in the field of aerospace medicine frequently use the term G. This term is the cause of the above-mentioned confusion. The unit G represents the total reactive force divided by the body weight and resisted gravitational acceleration ($G = F/W = ma/mg = a/g$). It is thus a dimensionless ratio of both force and acceleration. It is a vector and therefore has direction. This relationship of force and weight explains why a G meter of an aircraft at rest on a runway will indicate 1 G in the absence of any acceleration. Under sustained acceleration conditions, one can determine the amount of force by multiplying G by the weight W of the body ($F = GW$).

Impact acceleration is defined as a short-term or transient acceleration that is not sustained long enough to result in a significant constant or steady state component in the mechanical response by an accelerated body. The response in the human body is largely biomechanical, i.e., the accelerated body must be compressed, rearranged, or otherwise mechanically affected by the acceleration (Brinkley & Raddin, 2002). Various parts of the impacted body will experience somewhat different accelerations in response to an impact.

When describing the direction of the acceleration or the G vector, numerous coordinate systems have been used to describe physiological acceleration and the physiological reaction to acceleration, as shown in Figure 7.5.1-1 (Parmet & Gillingham, 2002). The coordinate system used here is a right-hand coordinate system that describes linear and angular acceleration directions with respect to the human Body. A +z axis acceleration acts headward and parallel to the spine of an individual. An acceleration acting perpendicular to the z axis, from back to chest, is +x axis acceleration. The + y axis is mutually perpendicular to the x and y axes, with acceleration acting from right to left.

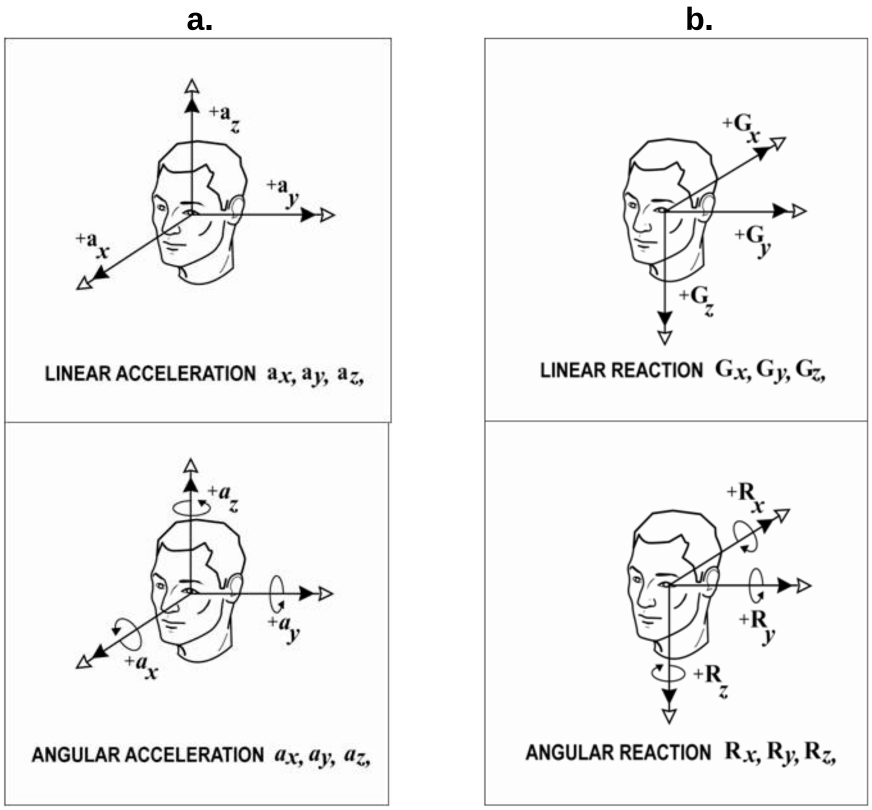

Figure 7.5.1-1. Acceleration (a) and Gravito-Inertial (b) Coordinate Systems

The physiological reaction to acceleration is often described within a gravito-inertial (G) coordinate system, as shown in Figure 7.5.1-1b. This coordinate system uses a backward, inverted, right-hand rule. Notice that the +Gy axis within the gravito-inertial coordinate system is not in agreement with the third law of motion with respect to the linear and angular acceleration coordinate system. This source of potential confusion makes it necessary for authors and speakers to clearly describe the coordinate system they are using.

The directions of the angular displacements, velocities, and accelerations are shown in Figure 7.5.1-1a. Note that the angular reactions in the gravito-inertial coordinate system correspond to the acceleration coordinate system. It is important to be aware that the coordinate systems used to describe acceleration or inertial response vectors usually do not correspond to the coordinate systems used in aerospace systems.

7.5.2. Application of Impact Force

The manner in which an impact is applied may be categorized in terms of penetrating impact, blunt impact, and whole-body impact. If the area over which the impact occurs is small and/or if the tissue is fragile, the contact force may cause penetration into the impacted body. Vehicles, seats, and personnel equipment should be designed to eliminate trauma from penetrating impact. Nonpenetrating impact applied to a specific area is referred to as blunt impact. Blunt impact is the common means of force application for restrained occupants of vehicles. The blunt impact forces are typically applied to a vehicle occupant by means of the seat surfaces, restraints, or

some combination of these factors. Localized blunt impact to inadequately restrained body parts may occur when a body part strikes a fixed surface such as an instrument panel or a seat.

Impact injury results from distortion of body structures beyond their recoverable limits. This distortion, termed strain, is a result of stress within the structures. Stress is defined as force per unit area. Strain is equal to force divided by the area of the applied force. There are different kinds of stress that can be applied to a body part. These are compression, tension, bending, shear, and torsion. Shear stress is produced by a nonaligned force-couple, which varies with cross-sectional area (Raddin, 1997). Stress is relatively independent of material characteristics. The material characteristics, however, determine what an object will do when subjected to stress. Any stress will produce some strain. The various types of strain responses to stress are formalized in dimensionless units expressing either a ratio of the change of length or a trigonometric function of the distortion angle associated with bending.

The human body responds to applied forces by a combination of acceleration and strain. Accelerations are force dependent and are determined by the ratio of force to mass. Strains or deformations are stress dependent and are determined by the ratio of force to area and by the viscoelastic properties of the affected body tissues. To avoid injury, impact acceleration must be applied over the appropriate times to produce the required velocity change while minimizing strain. Strain is associated with injury (Brinkley & Raddin, 2002). The apparent adverse effects of strain occur at the points of stress application. These include contusions, lacerations, and joint injuries. Acceleration of the body or its parts may also cause injuries at more distant locations from the point of application of force such as fractures within the spinal column during ejection acceleration.

The factors influencing human tolerance to impact acceleration are multiple. They include acceleration direction, amplitude, rise time or rate of onset, duration, velocity change, area of application of impact force, and limb flail. Human tolerance to impact acceleration has been defined in several ways. First, it may be described in terms of the maximum acceleration or applied force that does not result in significant injury. Second, it may be the point at which a volunteer subject is unwilling to continue to be subjected to higher acceleration. And third, it may be the point at which an experienced physician decides to end further exposure on the basis that measured physiological responses may be indicators of impending injury. However, as suggested by Brinkley and Raddin (2002), a given level of impact may result in no injury for one subject and death for another, so these definitions are vague at best. As mentioned earlier, the most common application of our understanding of impact acceleration is in aircraft escape systems, which will be discussed in the subsequent sections.

7.5.3. Historical Background of Emergency Escape Systems

Prior to our entry into World War II, the Germans anticipated crewmember escape from high-performance aircraft and initiated the development of a ballistic catapult ejection system, which was successfully installed in aircraft as early as 1941 (Henzel, 1967). In 1942 the German test pilot of a Heinkel HE-280V-2 prototype became the first pilot to eject to escape a crash (Tuttle, 2002). By the end of WWII, approximately 69 ejections had taken place from several different German aircraft (Billings & Treadwell, 2000). Concerned about escape from fighter planes, the U.S. Army Air Corps at Wright Field, OH, began investigating German technology such as

the Me-162 seat (Fig. 7.5.3-1), and in 1946 the first live ejection in the U.S. took place when First Sgt Lawrence Lambert ejected from a P-61 aircraft at Wright-Patterson Army Air Base in Ohio (Tuttle, 2002). The U.S. Army Air Corps soon began incorporating ejection seats into aircraft such as the XP-84 (1946) and the XB-47 (1947), and in 1951 the B-52 was built to incorporate both upward and downward ejection seats. In those early ejection systems, the pilot had to manually initiate the ejections, including canopy removal, pulling the armrests up, unbuckling the seat belt, and pulling the parachute ripcord (Billings & Treadwell, 2000).

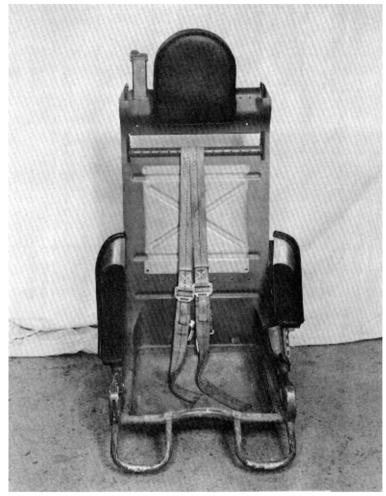

Figure 7.5.3-1. Early Ejection Seats Included the German Me-162 and United States P-84

During the 1950s, ejection began to be more automated with simplified handle pull and automatic canopy jettison, lap belt release, and parachute deployment. Also during this period, so-called "zero-zero" ejection systems were being developed by Martin-Baker to provide the capability for successful escape at zero airspeed and zero altitude (ground level) (Billings & Treadwell, 2000). In 1955, test pilot George Smith became the first person to survive an ejection at supersonic speed as he abandoned an F-100 at Mach 1.05. During the 1960s the use of encapsulated ejection seats was investigated and incorporated into the B-58 and XB-70 bombers. During the latter half of the 1960s, the F/FB-111 crew escape module system was also developed. Unfortunately, the lack of substantial low-altitude escape capability was a serious limitation of these systems. In addition, weight growth of crew escape modules due to avionics modifications caused serious parachute landing injuries.

7.5.4. Performance of Contemporary Ejection Seats

In the 1970s, the Advanced Concept Ejection Seat (ACES II), shown in Figure 7.5.4-1, was developed and flight qualified and included improvements such as simplified ejection controls, automatic escape sequencing, lightweight seat structure, and seat stabilization control. (Billings & Treadwell, 2000; Billings & Sadler, 2009).

When the ejection initiation controls of the ACES II ejection seat are actuated, a sequence of events is automatically initiated, including powered shoulder harness retraction, aircraft canopy jettisoning, ejection catapult ignition, and recovery system sequence power. As the seat enters the airstream, pitot tubes mounted on each side of

the headrest and parachute container and an internal static pressure barostat sense the aircraft speed and altitude. The recovery sequencer uses these measures to select the mode of operation appropriate for the environmental conditions.

Figure 7.5.4-1. ACES II Ejection Seat

As the seat separates from the ejection rails of the aircraft, a gyro-controlled rocket is ignited to control the pitch attitude of the seat. On some aircraft installations, a trajectory divergence rocket is ignited. The remainder of the recovery system sequence depends upon the mode that has been selected. The modes of ejection are shown in Figure 7.5.4-2 as functions of pressure altitude and knots equivalent airspeed (KEAS).

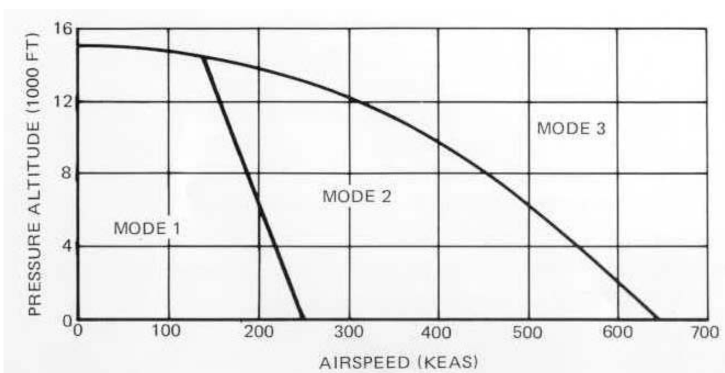

Figure 7.5.4-2. ACES II Ejection Seat Ejection Modes

In mode 1, the recovery parachute deployment is initiated 0.2 s after the rocket catapult is initiated. A mortar propels the parachute container away from the seat, parachute reefing line cutters are actuated, and a recovery system pilot chute is deployed. The parachute is deployed and inflated to a reefed condition until reefing line cutters are actuated to permit full inflation. In mode 2, as the seat approaches the top of the rails, a drogue parachute is deployed to decelerate the seat. Then after release of the drogue parachute, the recovery parachute is deployed and seat-occupant separation occurs. In mode 3, the sequence is the same as in mode 2 except the

deployment of the recovery parachute is delayed until the seat descends or decelerates to the mode 3 boundary condition (McDonnell Douglas, 1992; Billings & Treadwell, 2000).

The ACES II is the seat used in the majority of USAF fighter aircraft including the F-15, F-16, F-117, F-22, A-10, B-1, and B-2 and can now accommodate pilots in the range of 103-245 lb (Moore & Hampton, 2001). During the period from 1978-2007, there were 431 USAF ACES II ejections, with a survivability rate of 91%. All but three were from the F-16, F-15, A-10, and B-1B aircraft (Air Force Safety Center, 2007). The results of ACES II ejections for the period of August 1978 through September 2007 are summarized in Table 7.5.4-1.

Table 7.5.4-1. USAF ACES II Ejection Aircraft Type and Survival Rate, Aug 78 – Sep 07

Type	Total	Survived	Rate (%)
F-16	281	261	93
F-15	75	69	92
A-10	52	42	81
B-1B	20	19	95
F-117	2	2	100
F-22	1	1	100
Total	431	394	91

Significant improvements have been made to the ACES II seat over the past two decades. Additional improvements have been proposed but not yet implemented. The improvements are based upon advancements in escape system technology developed through the CREST (Crew Escape Technology) advanced development program, the Fourth Generation Escape System Technologies Demonstration Program, and the Cooperative Modification Program (CMP), as well as through other ACES II design modification efforts.

These improvements have included the digital recovery sequencer, limb restraint, windblast protection, and expanded weight range accommodation. These improvements have resulted in an in-envelope survival rate of over 95% (Billings & Treadwell, 2000) and a fatality rate per 100,000 flight hours that has approached zero in recent years, as shown in Figure 7.5.4-3 (Air Force Safety Center, 2007).

In particular, the CMP addressed concerns with the ACES II seat due to the large variation in weight and size among the aircrew population, including the headrest position, head impact attenuation capability, inertia reel strap angles with respect to the largest and smallest aircrew, canopy breaker position relative to the helmet on the largest aircrew, and limb restraint and seat stability for all aircrew. A modular seat now being tested is expected to replace the current structure with one able to be constructed in its final design in the aircraft and includes an adjustable headrest with energy attenuation to prevent head injuries (Ross et al., 2006).

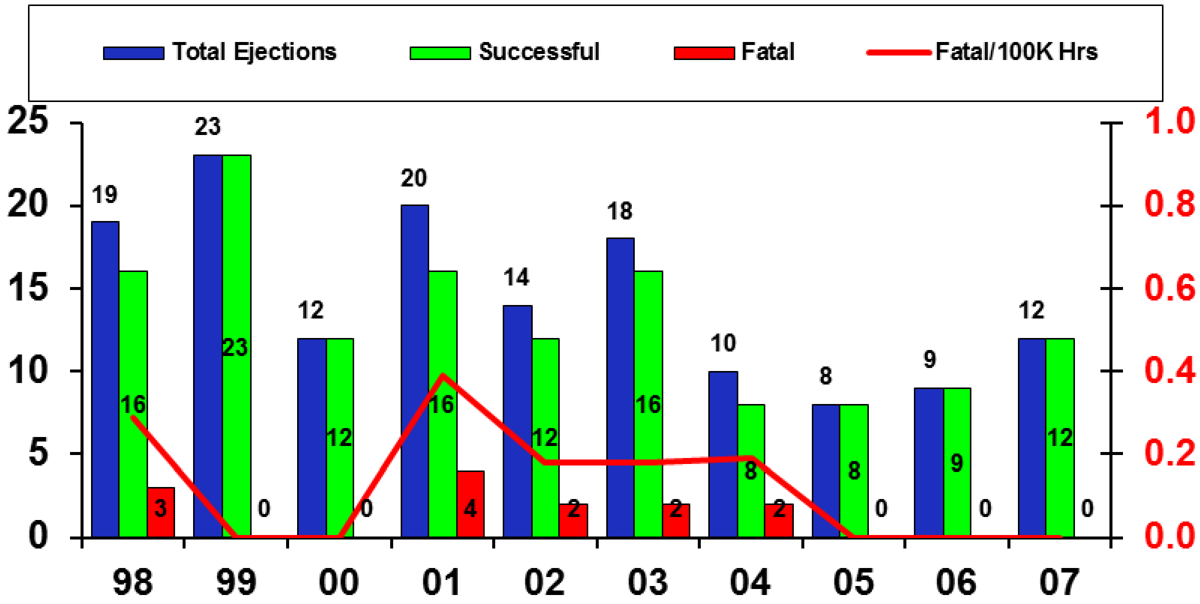

Figure 7.5.4-3. ACES II Aircraft Ejections, 1998-2007

7.5.5. Accelerations Occurring During Emergency Escape

An ejection is not a single event but is actually a series of events that are initiated when the crewmember pulls the ejection handle and includes rapid retraction with occupant restraint or **"**haulback," ejection catapult launch, rocket acceleration, windblast exposure, parachute opening shock, and ground landing. During all these phases, the crewmember may experience potentially traumatic impact accelerations.

7.5.5.1 Haulback. During this phase, the upper torso is repositioned to align the spine with the back of the seat to reduce the potential of spinal injury during ejection and protect against injury caused by windblast. The crewmember is first pulled back into the seat by a powered inertia reel. During haulback into the seat, the head may impact the headrest, particularly if the occupant is wearing a weighted helmet (Pint & Buhrman, 2000). The current USAF standard requires that repositioning before ejection must be completed in less than 300 ms (Air Force MIL-R-8236F, 1995). However, more recent studies have shown that upper torso retraction can be completed safely in about 200 ms, even with 4.5 lb of helmet weight, although females may be more at risk of neck injury under these conditions (Pint, 2003).

7.5.5.2 Catapult. The ejection catapult acceleration occurs after the ejection sequence is initiated. It occurs in two phases. During the first phase, a ballistic charge at the base of a telescoping tube fires and propels the seat and its occupant vertically up the guide rails. The second phase occurs as the seat reaches the end of the guide rails, when a rocket is ignited to further accelerate the seat and occupant to a height to adequately clear the vertical stabilizer of the aircraft and, at low altitude, to provide adequate height for safe recovery parachute deployment and occupant descent.

The accelerative force associated with the first phase of the catapult operation acts parallel to the spinal column. An ejecting crewmember may experience anywhere

from 10 to 20 G, depending on the type of ejection seat, the mass of the crewmember, the propellant temperature, and variance in catapult performance (Raddin & Brinkley, 2005). The acceleration vector of the rocket is directed through the center of gravity of the seat and occupant combination by the rocket nozzle.

Human tolerance levels during catapult operation are understood to be just below the point where irreparable damage would occur in the most vulnerable component of the vertebral column. Studies using cadavers have shown that the vertebral endplates and vertebral bodies are the tolerance-limiting components of the axially accelerated spinal column. Cadaver studies have also shown that the thoracic-lumbar region of the spine is most prone to injury during ejection (Henzel, 1967). U.S. Air Force operational experience has supported this finding. The crucial biodynamic factors that determine the severity of loading on the vertebrae during acceleration are the rate of onset of acceleration or rise time to peak acceleration, the maximum acceleration that occurs during the length of time that peak acceleration is in effect, and the time period of the acceleration.

Neck injury due to severe cervical compression or flexion can also occur during the catapult phase of ejection. There are several nonfatal fractures that can be caused by the compression forces encountered during ejection. These fractures have been categorized as fractures of the vertebral body margins, anterior wedge fractures, lateral wedge fractures, and cleavage fractures of the centrum. The most common ejection neck injury is the anterior wedge fracture, which is classified by the collapse of the frontal part of the vertebral body and is normally in the C5-T1 region. This fracture is benign in most instances and total recovery is likely, although there may be considerable pain and discomfort that may result in at least 2 mo of disability (White & Panjabi, 1990).

7.5.5.3 Windblast. As an ejection seat and its occupant are accelerated out of the cockpit during escape from a high-speed aircraft, the occupant is exposed to a combination of the ejection catapult acceleration and the aerodynamic pressure of the wind stream surrounding the aircraft, windblast. The resulting aerodynamic forces are defined with respect to the flight path of the seat. The force acting along the flight path to decelerate the seat is called drag. The upward and side forces are called lift. Forces that may cause a change in the angle of the seat and occupant are called moments. The wind stream produces drag, lift, and moments that increase as a function of the aerodynamic pressure, q, which is proportional to the air density and the square of the wind stream velocity, and to a lesser degree other factors such as air viscosity and elasticity. The drag that is produced is determined by the area and shape of the seat and occupant relative to the flight path. If the aerodynamic forces and moments dislodge the arms and legs, they can be injured when the joint strength is surpassed or the long bones are fractured after coming into contact with the seat (Specker & Brinkley, 1983). In most ejection seats, only the torso is restrained, leaving the arms and legs to flail and sustain injury at high airspeeds. This has been rectified in aircraft such as the B-1 bomber and F-22 fighter by the use of arm and leg restraints that are deployed during the initial phase of the ejection sequence. But as with any safety device, the success of the feature is only manifest when the ejection sequence is initiated within the known envelope of operation.

Another potential mode of injury during the windblast phase of ejection can occur when the crewmember ejects while the aircraft is traveling at a high rate of speed, causing the resulting high wind velocity to violently push the head backwards into the

headrest (Figure 7.5.5-1). Serious head injuries such as concussions and brain hemorrhages can be the result. This phenomenon is more likely to occur in ACES II seats where there is a relatively large angle between the seat back and rails, such as in the F-16, and can be exacerbated by the crewmember wearing weighted helmets and not bracing the head properly against the headrest.

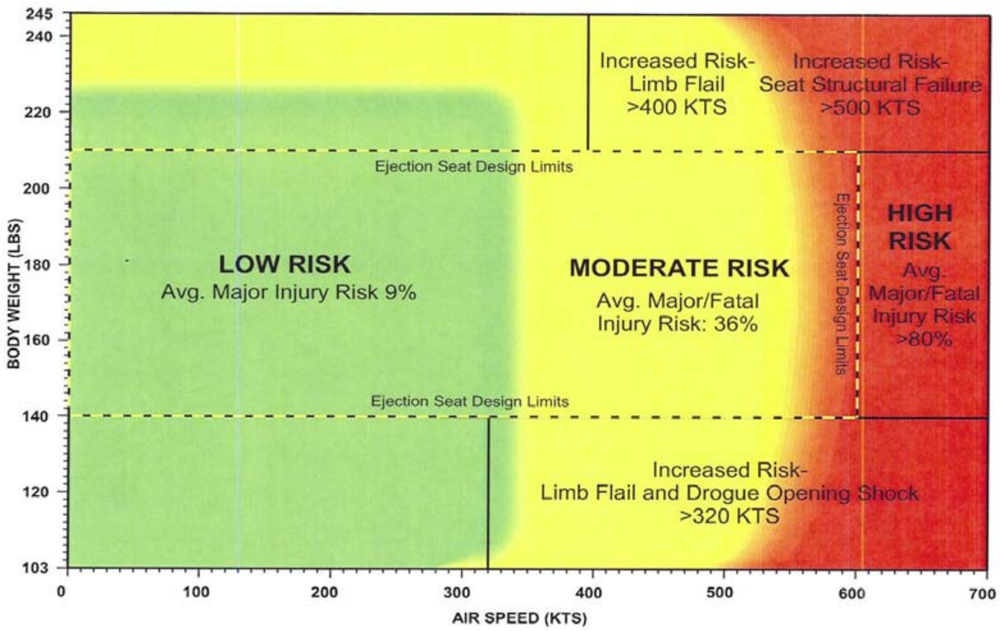

Figure 7.5.5-1. ACES II Ejection Injury Risk

The majority of USAF ACES II ejections over the past decade took place at airspeeds between 50-400 IAS (indicated airspeed). IAS is the airspeed read directly from the airspeed indicator on an aircraft. As shown in Table 7.5.5-1, the occurrence of major and fatal injuries increases at airspeeds greater than 300-350 IAS, with 100% of ejections at or above 450 IAS resulting in major or fatal injuries (Air Force Safety Center, 2007).

Table 7.5.5-1. ACES II Ejection Airspeeds and Injuries, 1996-2007

Airspeed (IAS)	Total Ejections	Fatal Injuries	Major Injuries	% Major & Fatal Injuries
0-49	3	0	0	0
50-99	14	2	1	21
100-149	22	0	3	14
150-199	43	0	3	7
200-249	23	0	0	0
250-299	9	0	0	0
300-349	7	1	3	57
350-399	9	2	0	22
400-449	1	0	0	0
450-499	3	2	1	100
500-549	2	0	2	100
550-599	3	2	1	100
600+	3	2	1	100
Total	142	11	15	18

When the crewmember encounters windblast, extreme lift and side forces and moments acting on the head and neck can cause damage to the cervical spine (Specker & Brinkley, 1983). For example, the airflow over the curved surface of the helmet decreases the pressure above the helmet, producing a lift force as the seat enters the air stream. Air pressure entering under the helmet may add to this lift force. The lift force at very high speeds is often enough to overcome the inertial loading on the helmet due to the ejection acceleration, causing the helmet to lift up on the head and neck. This causes a large force to be applied to the crewmember's neck until the windblast diminishes or the helmet breaks away. The airflow also applies a drag force, pushing the crewmember's head backwards into the seat (Pellettiere, 2003). Recently developed neck injury probability curves predict a 5% probability of neck injury for tensile neck forces of 520 lb for large crewmembers and 390 lb for small crewmembers (Carter et al., 2000).

In the past, helmets were supplied with a chinstrap that could, under certain load conditions, permit the helmet to separate from the crewmember during ejection. However, new straps such as the integrated chin-nape strap (ICNS) have been designed to stabilize the helmet and improve retention (Pellettiere et al., 2005). Although the ICNS has the potential to increase helmet retention and stability when additional helmet equipment is added, tests demonstrated that increased neck loading occurred when a helmet using the ICNS was used (Pellettiere, 2003). To reduce the risk of neck injury due to helmet retention, the breakaway integrated chin-nape strap was proposed, which is designed to release the helmet after a certain point to maximize helmet retention while minimizing the risk of neck injury (Pellettiere et al., 2005).

7.5.5.4 Seat Deceleration. After the ejection seat travels vertically up the guide rails and clears the cockpit ejection rails, the seat decelerates horizontally due to aerodynamic drag of the seat and its occupant and opening of the drogue parachute attached to the seat. The drogue parachute is a small, strong parachute that inflates quickly, resulting in an immediate decelerating force (Wittendorfer, 2003). The primary functions of the drogue parachute are stabilization and deceleration under high-speed escape conditions and stabilization during descent from high altitude (McDonnell Douglas, 1992).

The horizontal deceleration of the seat resulting from the overall drag force can be as high as 44 G. In high-speed ejections, the windblast will force the occupant's head back against the seat headrest, thus mitigating much of the head and neck flexion and neck loading due to the seat deceleration. However, at lower airspeeds, the deceleration of the seat can be sufficient to cause head and neck flexion. If hyperflexion of the neck occurs, it could generate excessive tensile loads in the neck similar to those seen during automobile frontal impacts (Pellettiere, 2003). Flexion injuries are assumed to occur when the head and neck are forced forward past normal limits and include sprains, fractures, and facet dislocations (White & Panjabi, 1990).

7.5.5.5 Parachute Opening Shock. Parachute opening shock (POS) occurs during the phase of ejection when the parachute opens and the ejecting crewmember decelerates suddenly. One of the possible effects of POS is whiplash, as occurs in car crashes. The precise means of injury during whiplash is not definite; however, it is usually considered to involve hyperextension (White & Panjabi, 1990). Symptoms such as pain, torn muscles, ligament damage, joint injuries, and bone damage have been reported during this phase (Mertz & Patrick, 1967). These injuries are rare in the

current ACES II seat, but a number of neck injuries did occur in the escape seat that was installed on several fighter aircraft prior to their being fitted with the ACES II seat. The potential for neck injuries also still exists in some older ejection seats that are still in use, such as those in the B-52, which have high catapult accelerations. This is of particular concern if the ejecting crewmember is a small female and/or is wearing a weighted helmet system.

To avoid harmful parachute opening shock injury to the crewmember and major damage to the personnel parachute canopy, the parachute must not be opened at high altitude. Contemporary escape systems and parachute opening devices are designed to prevent opening above 14,000 to 15,000 ft. As more crewmembers are equipped with helmet-mounted devices (HMDs) that increase the neck-supported weight and alter the head/helmet center-of-mass, the number of neck injuries due to POS throughout the Air Force is expected to increase. To minimize the risk of these type injuries, it is recommended that the weight of helmets with HMDs be kept under 5 lb with minimal shift in the center-of-gravity (Doczy et al., 2004).

7.5.5.6 Landing. Approximately 40% of all nonfatal injuries related to ACES II ejections happen while landing (Air Force Safety Center, 2007). The principal injuries reported due to landing impact include leg/ankle fractures and spinal fractures. A review of F/FB-111 aircraft ejections from 1967-1980 shows that 11 out of 23 injuries that were incurred during successful ejections by 78 crewmembers were due to ground landing. The mechanism responsible for these injuries was deemed to be axial compression and flexion (Hearon et al., 1981). Injuries such as severe abrasions and fractures can also occur when the parachute and parachutist are dragged by the wind across the terrain (Ejection Seats, 2007). While ankle injuries are the most predominant landing injury in both civilian and military parachutists, other lower extremity injuries can also occur and include sprains of various ligaments and muscles as well as foot and leg bone fractures. Extreme impact forces and moments, mostly due to poor landing techniques, cause these injuries.

The landing technique used by experienced parachutists is the parachute landing fall, which is designed to decrease the impact force and injury by increasing the amount of time used to absorb the impact and by distributing the impact over a larger area of the body (Kong et al., 2002). Other factors influencing the likelihood of injury are the parachutist's prior ejection experience and the landing attitude with respect to the direction of horizontal drift (Madson, 1975). Parachute landing impact injuries are also heavily dependent on aircrew weight and descent rate.

7.5.6. Crew Protection

Other important factors influencing the likelihood of injury during ejection include the ejection seat configuration, the crew restraint system, and the seat cushion. Before each takeoff, the crewmember must be firmly strapped into the seat to avoid excess body movement and seat cushion compression during an ejection. The restraint harness and other mechanisms of reducing limb flailing must be properly attached and fastened. The helmet visor must be in the proper position to protect the eyes, and the helmet must be properly fitted and secured to avoid injury to the eyes, head, and neck from windblast during ejection (Ernsting et al., 1999). Proper training in ejection procedures will reduce many potential hazards during ejection, such as:

- Delay in decision to eject
- Improper body position prior to initiating the ejection sequence
- Aircraft orientation to optimize the potential for success

7.5.6.1 Seat Configuration. Aircraft ejection seats are configured with varying offsets between the seat back angle and the catapult rail angle that can either mitigate or increase spinal injury risk during upward ejection. For example, the ACES II seat back has a forward offset of 4°-7° with respect to the catapult rails, depending on the type of aircraft. With seat back angle inclined forward as little as 5°, injury risk would likely increase slightly due to increased head x axis acceleration, increased head angular acceleration, and increased chest z axis acceleration (Perry et al., 1991). Conversely, studies have shown that aircraft ejection with the seat reclined 20° from the vertical rails would result in lower spinal/neck injury risk compared to the upright position, as demonstrated by lower compressive upper torso and head shear accelerations and lower seat pan force (Brinkley et al., 1981).

Another consideration is the offset of the headrest with respect to the seat back. USAF ACES II headrests are mounted in-line with the seat back, while headrests on most seats used by the Navy are mounted at least 2 in. forward from the seat back to provide pilots with better vision of the cockpit instruments during catapult launches from aircraft carriers. The forward-mounted headrests generate greater neck flexion during upward ejections, especially when the pilots are wearing helmets with forward-mounted devices, and may contribute to greater injury risk due to higher neck loads. This is consistent with laboratory test results that have demonstrated statistically significant increases in maximum horizontal head displacements in human subjects during vertical impact tests with the headrest positioned 2.25 in. forward of the seat back plane (Brinkley et al., 1982). However, a positive benefit of forward-mounted headrests is that they may act to decrease the magnitude of head impact caused by the head accelerating back from the initial neck flexion and striking the headrest. Conversely, rearward offsets of as little as 1 in. in the headrest during vertical impacts may predispose the occupant to cervical extension, possibly causing neck pain (Brinkley et al., 1982). However, Perry (2003) found that positioning the headrest 1 in. rearward while wearing heavy helmet systems allows the occupant to better control head/neck pitch during vertical impact, while not inducing significant rearward head rotation.

7.5.6.2 Restraint System. An effective restraint system should minimize the transmission of loads to the occupant as well as control the occupant motion with a minimum of contact stress. The lap belt alone provides a relatively low level of impact protection and may slip over the pelvis and against the abdomen, causing the belt loads to be applied against the lumbar spine. The use of shoulder straps improves injury tolerance by increasing the restraint-bearing area, increasing the load paths into the torso, and reducing the relative motion between body parts (Brinkley & Raddin, 2002). Experiments using dummies and volunteer human subjects have been carried out to assess the effect of the attachment angle of shoulder straps on human dynamic response. Shoulder harness angles of less than 0° relative to the horizontal plane of the aircraft have been determined to be a contributing factor in the spinal injury rate. A negative angle will cause vertical compression loads as a reaction to horizontal forces carried by the shoulder straps (Brinkley et al., 1979). A shoulder harness angle of 25°

has been shown to minimize seat pan loads and head accelerations as compared to an angle of 0° (Kuennen et al., 2003).

Another area of concern in restraint system design is the placement of the lap belt tie-down points. Laboratory studies with human subjects have demonstrated an increase in head accelerations and seat pan forces during frontal impacts when the tie-down points are mounted directly below the seat back/seat pan intersection as compared to mounting the tie-down points 3 in. aft of this location. The greater head accelerations and seat pan forces could contribute to an increase in the risk of neck or spinal injury during the main parachute opening phase of ejection. However, this more forward location may have the beneficial effect of decreasing the potential for the occupant's torso to slip under the lap belt, also known as "submarining" (Kuennen et al., 2003).

7.5.6.3 Seat Cushions. The seat cushion most commonly used in the ACES II ejection seat is composed of two layers: a top layer of rate-dependent foam and a bottom layer of polyethylene foam (Perry et al., 2000). Although seat cushions may provide comfort during long missions, the likelihood of vertebral fracture may increase depending on the rate of cushion deformation. The cushion can magnify the impact reaction by delaying the beginning of acceleration of the individual or by collecting and then releasing energy elastically during recoil. Either way, the individual in the seat encounters a larger change in velocity than the seat itself. Therefore, the benefits of better seat comfort must be weighed against the chance of spinal injury (Hearon & Brinkley, 1986). Vertical impact testing has shown that rate-dependent foam cushions transmit less energy because of their ability to reduce the amplification of impact acceleration as well as supply a comfortable seat cushion. The safety margin of the cushion is dependent upon both the cushion material and the cushion configuration (Cheng & Pellettiere, 2004).

7.5.7. Impact Injury Criteria

7.5.7.1 Spinal Injury Criteria. When the first ejection seats were developed, ejection catapult performance was evaluated in terms of the rate of onset of the acceleration and the maximum acceleration. This was a simple means of preventing spinal injury. However, as new escape systems such as the B-58 capsule and spacecraft such as the Mercury capsule were developed, the complex acceleration-time histories that were produced during the operation of these systems did not lend themselves well to simple characterization in those terms, or in the trapezoidal profiles that were suggested by others. As a result of the combination of this problem, experimental efforts, and an improved understanding of biomechanics, relatively simple mathematical models were proposed (Stech & Payne, 1969). These models involved the use of dynamic mechanical models to simulate the response of the human body to short-duration acceleration and to estimate the probability of injury. The Dynamic Response Index (DRI) model is one such model developed to estimate the probability of compressive fractures of the lumbar and thoracic spinal column due to upward acceleration during ejection. The model is a simple linear, lumped parameter mechanical model consisting of a mass, spring, and viscous damper. The dynamic response of the model is computed using its mathematical analog, a second order, linear differential equation, and then related to the risk of spinal injury.

The DRI model properties, damping coefficient ratio, and undamped natural frequency are based upon vibration and impact tests with volunteer subjects. These calculations are based on engineering formulae and are used in determining injury criteria during investigations of survivable crashes. The probability of spinal fracture was initially based upon the results of compression tests of cadaver vertebrae. The model was then validated by comparing the results of the analyses of ejection catapult accelerations of specific ejection seats to the injury rates experienced operationally by those specific escape systems (Brinkley & Shaffer, 1970). The validation process demonstrated that the operational injury rates were lower than predicted using vertebrae from cadavers. However, the probability distribution from the vertebral tests was found to be reasonable. The model and the resulting relationship between spinal injuryand the value of the DRI are shown in Figure 7.5.7-1.

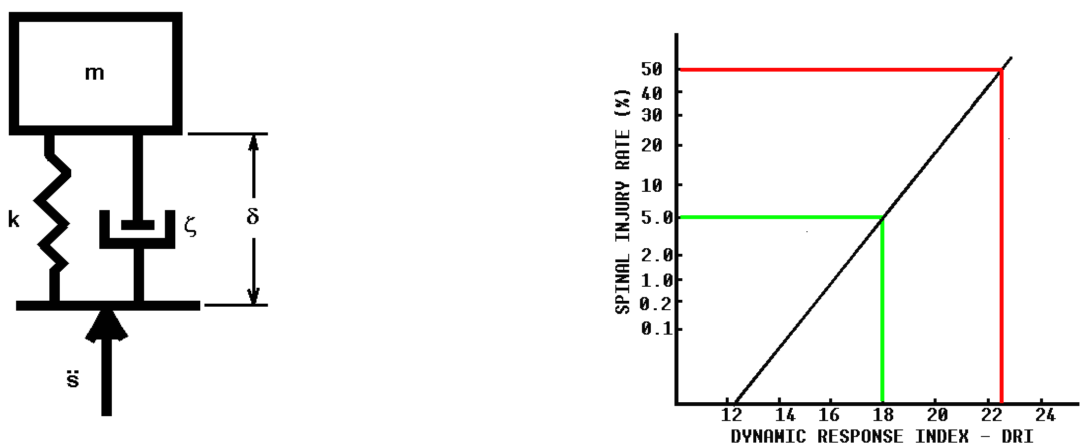

Figure 7.5.7-1. Dynamic Response Index (DRI) Model and Spinal Injury Rate

A similar approach was used to develop models for the other primary axes. Estimates for the likelihood of injury were made on the basis of experimentation with volunteers as well as accidental injuries (Brinkley et al., 1990). These models were then used to develop a method to evaluate multiaxial acceleration exposures. Each model was developed to compute a dynamic response (DR) value for each of the primary acceleration vectors, which could then be compared to preestablished injury risk levels (DR risk limit values) as shown in Table 7.5.7-1. The injury risk values were developed for the case where a seat occupant is restrained by a lap and two shoulder straps and a negative-g strap or similar restraint system configuration.

Table 7.5.7-1. Multiaxial Dynamic Response Injury Risk Values

+DRZ	-DRZ	+DRX	-DRX	DRY	RISK LEVEL
15.2	13.4	35	28	14	Low
18.0	**16.5**	**40**	**35**	**17**	**Moderate**
22.8	**20.4**	**46**	**46**	**22**	**High**

7.5.7.2 Multiaxial Dynamic Response Criteria. The multiaxial whole-body impact exposure limit method that was developed by the Air Force is known as the Multiaxis Dynamic Response Criteria (MDRC). The overall injury risk of multidirectional impact acceleration is obtained by dividing the computed DR values for each orthogonal axis (x, y, and z) by the DR limits, then squaring each result and taking the square root of the sum.

$$\beta = \left[\left(\frac{DRX}{DRXL} \right)^2 + \left(\frac{DRY}{DRYL} \right)^2 + \left(\frac{DRZ}{DRZL} \right)^2 \right]^{1/2}$$

The multiaxial acceleration of an ejection seat or a spacecraft seat and restraint system is determined to have surpassed the specific injury-risk level if the calculated value of the MDRC is greater than 1.0 (Brinkley et al., 1990).

Where injuries are of concern from extremity motion or blunt impact, other methods must be used to evaluate the likelihood of injury. The effects of impact acceleration of the head and neck are of concern. Methods that are used to evaluate the effects of automotive crash should be considered, but not without serious consideration of the differences between the automotive crash environment and that of the aerospace application. These include the impact profile, impact direction, seat, and restraint system. Clearly, there are major differences. Although the criteria cannot be applied in terms of absolute limits, the criteria may be of value when comparing alternative protection systems.

7.5.7.3 Automotive Crash Neck Injury Criteria. A method used to calculate automotive neck injury criteria is the N_{ij} method, developed by the National Highway Traffic Safety Administration (NHTSA). The neck injury criteria are composed of tolerance limits for axial loads (tension and compression) and bending moments (flexion and extension) determined in crash tests using dummies. These criteria are referred to as N_{ij} criteria, where the 'i' represents either tension or compression and the 'j' represents flexion or extension. The N_{ij} value must be less than or equal to 1.0 to have an acceptable load and bending moment. An N_{ij} value of 1.0 compares to about a 30% risk of serious injury (Kleinberger et al., 1998). These criteria are used mainly for evaluating the neck loads experienced by instrumented manikins during frontal automobile crash tests. A version of the N_{ij} method has also been used to evaluate effects of accelerations experienced during tests of aircraft ejection seats. The Air Force typically uses a lower N_{ij} criteria value of 0.5, which corresponds to an injury risk of 5%, when conducting simulated ejection tests.

7.5.7.4 Head Injury Criteria. The method used by NHTSA to determine the likelihood of skull fracture from direct impact with structures such as an automobile instrument panel is the Head Injury Criterion (HIC). This form of head injury criterion was first established by Gadd (1966). The weighted-impulse criteria were first used as the head impact Gadd severity index (SI), a means to describe the severity of a head impact with respect to the Wayne State Tolerance Curve (WSTC). The WSTC was developed by dropping cadaver heads onto flat surfaces. It provided a technique to establish a relationship between peak acceleration, pulse duration, and the likelihood of skull fracture and concussion that result from a linear impact. After the initial use of the SI, it was found that a more practical means of computation of the criteria was necessary. This resulted in the development of the HIC. The critical value of HIC is 1000, computed from accelerations measured within the head of a mid-sized male

automotive test dummy over a 36-ms time duration (Kleinberger et al., 1998). This HIC value has been related to a probability of skull fracture of approximately 48% (Hertz, 1993). A plot showing injury risk as a function of HIC values is shown in Figure 7.5.7-2.

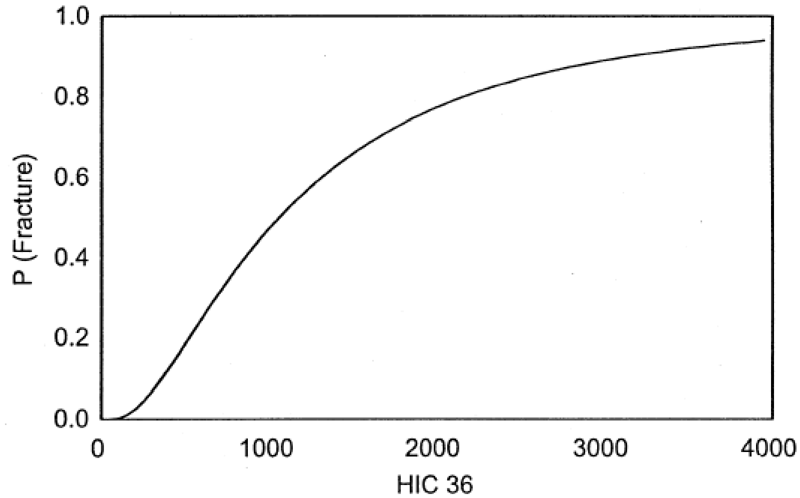

Figure 7.5.7-2. Injury Risk Curve for the HIC (Kleinberger et al., 1998)

7.5.8. Additional Injury Risk Factors

7.5.8.1 Gender. The Air Force pilot population now includes both males and females with a weight range of 103-245 lb and height range of 64-77 in. (Fig. 7.5.8-1), leading to concerns about both cockpit accommodation, which includes aspects such as overhead clearance, leg clearance, control stick operation, visual field, etc. (Kennedy & Zehner, 1995), and ejection injury risk to small occupants. Studies conducted at the Air Force Research Laboratory (AFRL) have determined that the biodynamic responses of males and females are not significantly different during either compression (Buhrman & Mosher, 1999) or frontal impact (Buhrman & Perry, 2000) and that the vertebral stress experienced in the thoracic-lumbar region is comparable for both genders during compression. Therefore, the parameters and probability curves used to calculate the Air Force's DRI injury criteria for lower spinal injury are probably valid for both genders. However, females do appear to be more at risk of neck or cervical spinal injury during impact acceleration events, such as those occurring during aircraft ejections. This is primarily a function of the higher dynamic stresses generated during ejection on their cervical vertebrae, resulting primarily from their smaller vertebral cross-sectional areas (Gallagher et al., 2007). Studies have also shown that females have less neck flexor and extensor strength when compared to males (Foust et al., 1973; Morris & Popper, 1996), which makes them less able to offset neck loading during preimpact bracing and, therefore, less able to withstand shear forces during -Gx impact accelerations (Doczy et al., 2004).

Figure 7.5.8-1. Photo Showing the Range of USAF Pilots' Size

7.5.8.2 Helmet-Mounted Systems (HMS). With the Air Force's emphasis on improving and developing new warfighting technologies, it is important to consider the effects of HMS during ejection. Helmet-mounted systems can include integrated helmet-mounted cueing systems, helmet-mounted night vision devices, and helmet-mounted aircraft display systems that may provide improved aircraft flight control, target acquisition, and weapon delivery. With the addition of one or more of these HMS, the helmet's inertial properties (weight, center of gravity, and moment of inertia) may be altered. If these HMS are being used during ejection, the possibility exists that the helmet's inertial properties will increase the rate of ejection-related neck injuries by increasing the dynamic forces generated in the cervical spine. The HMS may also affect the pilot's performance by increasing the fatigue of the posterior neck muscles that balance the head and affect the fit and comfort of the helmet (Perry & Buhrman, 1996).

Helmets weighing more than 5 lb with severe forward center-of-mass are not recommended due to the increased risk of neck injury and neck fatigue (Perry, 1998; Doczy et al., 2004; Caldwell & Gallagher, 2006). Current operational systems include the ANVIS 49/49, the joint helmet-mounted cueing system (JHMCS), and the panoramic night vision goggles (Fig. 7.5.8-2). Some of these helmet systems approach or slightly exceed the above recommended limits. AFRL is actively evaluating the safety, comfort, and performance effects of wearing these and other helmet systems, as well as investigating the potential for long-term chronic neck pain and injury in pilots wearing HMS over several months or years.

Figure 7.5.8-2. Pilot Wearing Panoramic Night Vision Goggles (PNVG)
(Air Force Link, 2007)

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Concepts

- Haulback
- Restraint system

Vocabulary

- Acceleration
- Advanced concept ejection seat (ACES II)
- Ejection catapult acceleration
- Impact acceleration
- Parachute landing fall (PLF)
- Parachute opening shock
- Windblast

7.6. Crash Survival

"We must never forget that we are working with men of flesh and blood and nerves." Major General Douglas Haig, 1903.

Lt Col Andrew D. Woodrow, USAF, BSC

7.6.1. Aircraft Crashes

If ejection (see section 7.5. Impact and Ejection) is not an option, occupants are only protected during an aircraft crash by aircraft design criteria and nature of the crash. The overriding requirement for all aircraft design is that of safety. The order of safety required is specified in the Airworthiness Requirements published by the U.S. Federal Aviation Regulations (FAR) and the European Joint Airworthiness Requirements (JAR). Despite all efforts to maintain safety in flight, some aircraft and crews fail, resulting in a crash. No two aircraft crashes are alike; one may be due to a loss of power and result in low velocity impact with ground, while others may be high speed impact with the water. Still others may relate to loss of control and in-flight break-up of the fuselage or a very hard landing resulting in airframe damage and occupant injury. In all cases, concern for protection of the passengers and crew is the primary goal of design and operation of aircraft.

7.6.2. Prior Planning to Reduce Injury During Unaided Escape

During planning for a flight, both crewmembers and passengers should consider some precautions and procedures that would increase their chance of surviving a crash.

- Consider the route of flight as well as the destination and plan clothing choices accordingly.
    - If route is over cold environments, bring a jacket onboard.
    - Avoid nonprotective clothing such as nylon, silk. or polyester.
    - Choose cotton, wool, or, even better, Nomex or other flame-retardant material.
    - Wear only flight-certified boots.
- Listen to the briefing.
    - Know the escape routes, primary and alternate.
    - Keep materials that could cause injury strapped in or as confined as practical.
- Keep seat belts fastened whenever movement about the cabin is not necessary.

7.6.3. Factors that Impede Escape and Survival

Statistical accident analyses have shown that the probability of aircraft crashes has diminished dramatically in the past decade; however, the percentage of persons killed in fire-related accidents has remained constant, at about 15%-16% over the past 35 years (Taylor,1989). After the initiation of an open fire in the cabin, heat, smoke, and toxic gases are produced, which are composed of soot and partially burnt hydrocarbons, carbon monoxide, fluorine, and cyanide compounds. Along with respiratory difficulties, the passengers will also face degraded visibility in the cabin;

transmission values of 20%-30% at 1.1 m above the floor can occur within the first 2 min following initiation of the fire (Winterfeld, 1992). Within 3 min, interactions are strong enough to incapacitate due to skin burns, loss of consciousness, or visual obstruction. External fires can also impede escape and evacuation. Evidence from aircraft accidents show that people react in a very competitive manner when confronted with a survival situation. Evidence suggests that this may disrupt orderly evacuation, especially in circumstances when visibility is reduced and there are obstructions like seats, bulkheads, cargo/baggage, or other passengers in the way. In military single- or dual-seat aircraft, there is the problem of an unassisted escape from an environment encumbered by additional restraint systems.

Another factor that influences the chance of survival or injury following a crash is the physical damage to the airframe or exit. Once impact is made, the frame of the fuselage may bend or warp, causing a reduced living space for occupants or an exit that cannot be operated. Evidence from wide-body aircraft crashes that resulted in multiple head and neck injuries reveals that the hull of the aircraft can flex or fracture into the livable space, yet spring back to near normal shape at the end of the crash pulse. Exits, whether a hinged door, hatch, or a canopy that raises and lowers, can be made useless by heat or structural damage. In cases of water landings or ditchings, there is often precious little warning time prior to impact. Accident investigation analysis indicates that in upwards of 80% of sea ditching accidents, the aircrew had less than 15 s warning. A typical example of short warning time comes from a Canadian Forces Sea King mission:

> *The Sea King took-off for a water landing training mission. After initial sequences had been demonstrated including a single engine take-off, the student pilot then carried out a single engine landing and attempted a single engine take-off by himself. The take-off had to be aborted due to low rotor rpm and when rotor rpm recovered, the instructor directed the student pilot to continue the take-off. During the second attempt, rotor rpm again dropped before an abort could be executed, the aircraft struck the water nose down at approximately 20-25 kts ground speed. The aircraft pitched forward, severing its tail pylon, and came to rest inverted in 20 feet of water.*

Because the engine and transmission of a helicopter are on the top of the fuselage, the problem of capsizing compounds the efforts of safe escape. The fact that water, usually cold, rushes into the cabin and creates a darkened environment can lead to disorientation during escape. Additionally, if the occupants are not wearing protective clothing or life vests and are unsecured from harnesses or restraint systems prior to impact, the effectiveness of finding and using an emergency exit or egress point is reduced. In fixed wing examples, like the ditching of the Airbus 340 in the Hudson River in January 2009, the aircraft often floats well, providing more time for passengers and crew to find an exit and safely egress the aircraft. It is interesting to note that few, if any, of the passengers or crew wore a life vest or exited with the seat flotation cushion despite a highly likely egress into water.

In any case of emergency egress from an aircraft, the element that often leads to failed escape is "rule-based behavior." Every set of events that can be anticipated has been considered and reduced to a set of procedures or rule-based behaviors for the crew or passengers to follow (Green, 1996). These are not motor memory actions but rather a series of preconditioned "rules" formed and stored in long-term memory. Unlike other aircraft emergency situations that may afford time to reference documented

procedures, aircrew practice emergency procedures such as egress and escape to minimize the time to respond. One of the most common rule-based behaviors observed during egress of nonaircrew on multiplace aircraft is the use of the primary exit rather than the closest exit, a result of using a single entry point in 99% of all previous flight experiences.

Although the ditching depicted in Figure 7.6.3-1 was highly successful, the physiologic hazards during any aided or unaided egress can be considerable. Injury is likely during any crash, and mobility is decreased accordingly. The presence of water, especially very cold water, reduces the chances of survival even if egress is successful due to hypothermia and drowning. A crash on land can add the physiologic hazards of temperature extremes, terrain altitude producing hypoxia, and an inhospitable environment that does not provide adequate water or access for rescue and treatment of injury.

Figure 7.6.3-1. US Airways successfully ditched in Hudson River, 2009

7.6.4. Human Tolerance to Impact: Proper Positioning During Impact

No discussion on body position during impact can be complete without a review of human tolerance to crash forces. The most common cause of injury during accidents is the very abrupt deceleration that occurs when an aircraft strikes the ground or water. On impact a passenger or crewmember seated in an intact portion of the aircraft is propelled forwards. Any object in the path of the body or limb will become a hazard. For example, if the knees strike the bottom of the seat in front, initial injuries to the knee, tibia, and femur often result. The impact forces are transmitted up the femur, driving it into the pelvis and resulting in pelvic fractures. Any lower limb injury that prevents a person from walking to an exit has a negative influence on successful egress. In terms of the physics of impact forces, the primary concern is centered on biodynamics, the response of the body to the magnitude, duration, and direction of acceleration. The kinetic energy that passes through the aircraft and internal objects will quickly exceed limits of strength and result in damage or injury.

MAGNITUDE is expressed as G, or multiples of the acceleration due to gravity.
DURATION (in crash analysis) is measured in fractions of a second.
DIRECTION is more complex because of the three axes of force but can be calculated using known conditions (e.g., forward facing, vertical impact).

In some cases the forces that reach the occupant are less than those applied to the airframe. Each aircraft part that collapses takes up some of the force, so peak G is reduced, helping to reduce the chance of injury. If any part of the restraint system allows movement of the occupant (head or limbs), protection from striking hard objects in the immediate environment must be designed. Investigations in the past have led to direct enhancements to the design of helmets, harnesses, and other personal protective equipment and the development of more crashworthy airframes.

The overall objective of designing for crash resistance is to eliminate injuries and fatalities in relatively mild impacts and minimize them in all severe but survivable mishaps. A crash-resistant aircraft will also reduce aircraft crash impact damage. By minimizing personnel and material losses due to crash impact, crash resistance conserves resources, is a positive morale factor, and improves the effectiveness of the fleet both in peacetime and in war. Results from analyses and research have shown that the relatively small cost in dollars and weight of including crash resistance features is a wise investment.

One accident that attracted attention from the National Transportation Safety Board, the Federal Aviation Administration, the Air Accident Investigation Board (UK), the aircraft manufacturer, and the seat manufacturer was the B-737 crash in 1985 at Manchester Airport in the UK (Fig. 7.6.4-1). Of the 126 occupants, 47 died as a result of the accident and a further 74 suffered serious injury (Carter, 1992). Although the aircraft sustained an impact lasting 2.2 s, the impact was broken into two segments, the first at the tail and the second as the nose impacted an upward embankment, resulting in the fuselage breaking in half and experiencing massive crushing. The causes of mortality and mechanical injury have been identified as crushing within a collapsing airframe, entrapment within the wreckage, being struck with loose objects, and absence or failure of restraint systems.

Figure 7.6.4-1. Tail Section of British Midland B737 at Manchester Airport

To provide as much occupant protection as possible, a systems approach to crash resistance must be followed. The systems approach to crash resistance means that the landing gear, aircraft structure, and occupant seats must all be designed to work together to absorb the aircraft kinetic energy and slow the occupants to rest without injurious loading. In addition, the occupants must all be restrained and a protective structural shell maintained around the occupied areas during a crash to provide a livable volume. Weapon sights, cyclic controls, glare shields, instrument panels, armor panels, and aircraft structure must be delethalized if they lie within the strike envelope of the occupant. Postcrash hazards, such as fire, entrapment, drowning, emergency egress, and rescue, must also be considered in an effective crash-resistant design.

Results of research on tolerance of the human body to impact forces are also discussed in section 7.5, Impact and Ejection. Although numerous experiments have been conducted and a wealth of information has been collected, very few criteria that may be useful in system design have been developed and validated. Those criteria that are generally accepted for practical application in assessing the crash resistance of an aircraft system were reviewed by Zimmermann & Merritt (1989). As discussed here, these criteria may be used to determine the acceptability of an aircraft or components, such as seats and restraint systems, based on the results of dynamic testing with anthropomorphic dummies or computer simulation.

A crash can involve a wide range of dynamic conditions, from a simple unidirectional impact to a complex combination of rotational and multidirectional impact conditions. Performance requirements under crash impact conditions for Army light fixed- and rotary-wing aircraft were reviewed by Zimmermann & Merritt (1989).

7.6.5. Attaching the Human to the Aircraft

One of the most important aspects of safety during crashes is the manner a passenger is harnessed to the aircraft, generally on a seat secured with a restraint system. Although military aircraft seats are not designed with maximum comfort in mind, it is worth a quick look at the evolution of the aircraft seat (Fig. 7.6.5-1). As air travel expanded through the 1920s and the commercial airline industry realized that revenue depended on returning customers, amenities driven at comfort took a “front” seat in the overall design of the aircraft. Safety and comfort are part of the design considerations for military aircraft, although comfort may take a “back seat” in many designs. Military aircraft are traditionally designed to a particular set of requirements that maximize payload while enduring rugged environments and conditions (Table 7.6.5-1).

Figure 7.6.5-1. C-130 Web Seating with Aluminum Supports (Left) and High-Density Foam Seats with Leather Exterior (Right)

Table 7.6.5-1. Seat User Groups with Physical and Cognitive Needs and Expectations (from Kovarik, 1999)

Seat User	Physical Needs and Expectations	Cognitive Needs and Expectations
Passenger	Safety and comfort	Can easily locate seat in aircraft
	Protection during survivable crash	Understand how to operate restraint system
Crew	Can reach and operate all controls	Know how to make minor adjustments and repairs in flight
	Protection during survivable crash	Know how to operate harnesses and stow seat
Maintenance	Safely clean and maintain seats	Procedures to repair easy to understand?
	Scheduled maintenance and repairs can be performed safely and easily	Maintenance procedures with standard assembly and tools?

Location of aircraft doors and hatches is a technical issue such as body loads, wing and engine mounts, limitations on escape slides, and configuration of the seats (Fig. 7.6.5-2). Regulatory requirements that guide certification authorities and designers are found in a series of Federal Air Regulations (FAR). Mission, certification, and standard requirements for aircraft ensure at least the minimum safety equipment and features are designed into the cabin. For instance, FAR 25.562, Emergency Landing Dynamic Conditions, states:

> (a) The seat and restraint system in the airplane must be designed as prescribed in this section to protect each occupant during an emergency landing condition when--
> (1) Proper use is made of seats, safety belts, and shoulder harnesses provided for in the design; and
> (2) The occupant is exposed to loads resulting from the conditions prescribed in this section.
>
> (b) Each seat type design approved for crew or passenger occupancy during takeoff and landing must successfully complete dynamic tests or be demonstrated by rational analysis based on dynamic tests of a similar type seat, in accordance with each of the following emergency landing conditions. The tests must be conducted with an occupant simulated by a 170-pound anthropomorphic test dummy, as defined by 49 CFR Part 572, Subpart B, or its equivalent, sitting in the normal upright position.

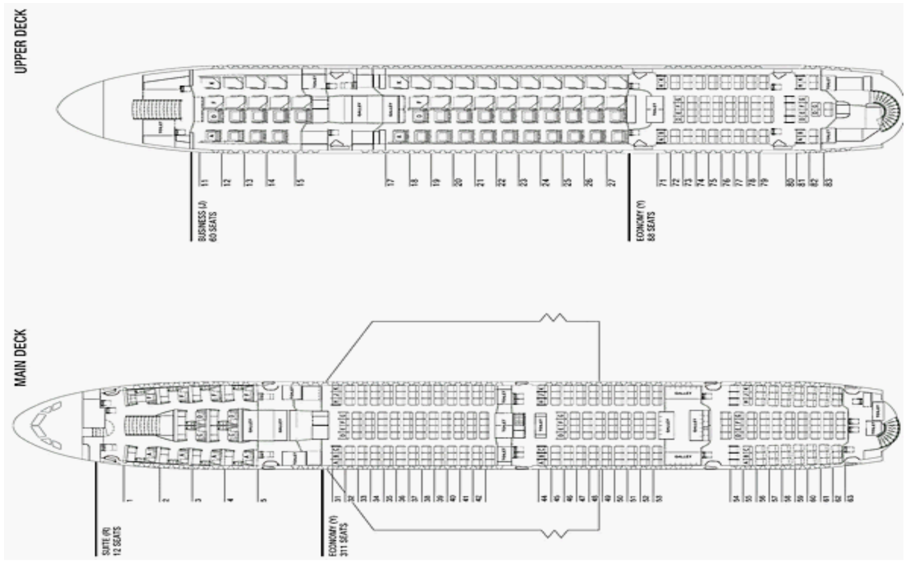

Figure 7.6.5-2. Singapore Airlines A-380 Configuration for 471 Crew and Passengers

From a design and configuration standpoint, survival from crashes is highly dependent upon the number of passengers, location and availability of exits (FAR 25.803, Emergency Evacuation; FAR 25.807, Emergency Passenger Exits; and FAR 25.813, Emergency Exit Access). Any design trade-offs for comfort must be considered against the minimum safety and survivability requirements.

7.6.6. Design Principles for Personal Restraint Systems

Restraint harnesses for personnel should provide the restraint necessary to prevent injuries to all aircraft occupants in crash conditions approaching the upper limits of survivability. Appropriate strength analysis and tests (Zimmermann & Merritt, 1989) should be conducted to ensure that a restraint system is acceptable (Fig. 7.6.5-3). Qualities that a harness should possess are listed below:

- It should be comfortable and light in weight.
- It should be easy for the occupant to put on and take off even in the dark.
- It should contain a single-point release system, easy to operate with one (either) hand since a debilitated person might have difficulty in releasing more than one buckle with a specific hand. Also, it should be protected from inadvertent release, e.g., caused by the buckle being struck by the cyclic control or by inertial loading.
- It should provide personnel with freedom of movement to operate the aircraft controls. This requirement necessitates the use of an inertial reel in conjunction with the shoulder harness.
- It should provide sufficient restraint in all directions to prevent injury due to decelerative forces in a survivable crash.
- The webbing should provide a maximal area, consistent with the weight and comfort, for force distribution in the upper torso and pelvic regions and should be of low elongation under load to minimize dynamic overshoot.

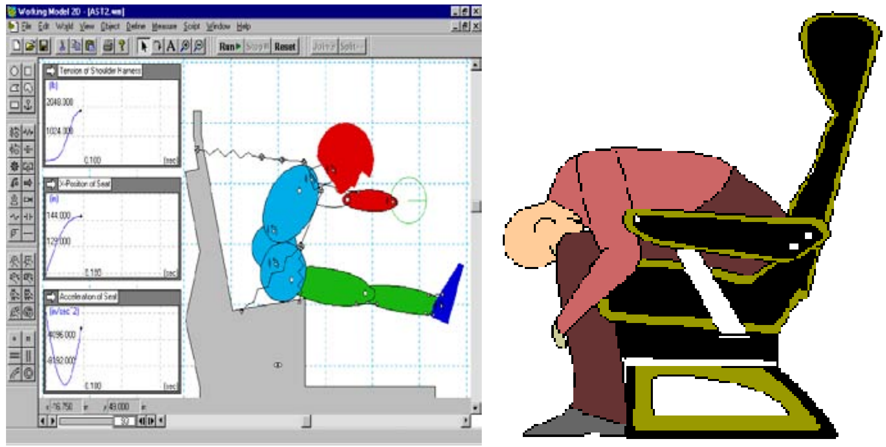

Figure 7.6.5-3. Seat Restraint Testing Completed with Crash Dummies or Computer Simulations Prior to Operational Test and Evaluation

7.6.7. Escape from Aircraft

As aircraft speeds and operational altitudes have risen, so, too, has the need to escape from the aircraft using assisted measures. The means for escape must be available at all times and must take into account the forces that may be operating on the aircraft, e.g., aerodynamic, accelerations, and rotations. Most high-performance military and training aircraft have ejection systems engineered into the cockpit (see section 7.5. Impact and Ejection). These systems use mechanical power for the escapee to leave the aircraft, whereas earlier, unassisted escape systems simply relied on physical strength. Ejection systems must provide sufficient thrust to eject the occupant clear of the aircraft structure at all reasonable operational speeds and attitudes and provide sufficient ground clearance to enable full deployment and inflation of the main parachute before ground impact. Modern systems are typically designed to be fully automatic once the ejection sequence is begun. Data analyses of RAF aircrew have shown a reduction in spinal injury rates compared with a previous RAF study of accidents where nonrocket-assisted ejection seats were used. In the earlier study the observed percentages of aircrew who sustained spinal fractures from RAF nonrocket-assisted seats were between 39%-69%. The current analysis demonstrates that the modification of the acceleration profile by the addition of the rocket motor has decreased the number of aircrew who have sustained spinal fractures (Lewis, 2006). There have been some attempts at engineering an automated system that would initiate the sequence if the occupant was unresponsive and dangerously close to the ground, but to date acceptance from the pilot community has been limited. The system should restrain the occupant sufficiently and modulate any forces on the body so that the risk of injury is minimized (Ernsting, 1999).

The initiation mechanism and ejection from the cockpit apply accelerations in excess of 12 G for up to 500 ms with an onset rate up to 300 G/s. The restraint system is of vital importance, as it retains the position of the escapee. A properly fitted restraint system increases the coupling with the seat and should minimize the possibility of "dynamic overshoot." This is when the person sits on an elastic cushion, and as the seat accelerates the cushion depresses until it is fully compressed. The seat can then impart a sudden high energy force resulting in a very high-amplitude, short-duration

impact, which may cause injury. Ideally the seat and occupant should be attached rigidly to each other so that the coupling moves as a single mass. This is impractical, and so, invariably, a well-damped thin foam pad is used between the occupant and the seat (Davis et al., 2008; Ernsting et al., 1999).

Another concern in aircraft escape, aided or unaided, is windblast. Within 0.2 s of the first movement up the rails of the ejection system, the seat and occupant are subjected to the full windblast while still traveling at approximately the same speed as the aircraft. The threshold of injury for blast is probably about 4.5 psi – equivalent airspeed of 440 kn – while serious damage occurs at about 8 to 9 psi – equivalent airspeed of 582-620 kn (Ernsting et al., 1999). Theoretically, very high blast pressures could lead to rupture of internal organs and death. The highest speed ejection in recent USAF record was from an F-15E; both the pilot and weapons system officer ejected at over 700 kn, and while the pilot survived with multiple severe injuries, the weapons system officer perished due to flailing injuries.

The precise procedure for bail out or unaided escape varies with the configuration of hatches and type of aircraft, but certain principles must be observed if the escape is to be successful. The first requirement is that the aircrew are correctly fitted with appropriate equipment and understand its operation and use. This is typically going to include a helmet, visor or goggles, parachute, and harness. They must be familiar with the escape sequence and know the location and method of egress from emergency exits, escape hatches, tunnels, or chutes. Unless these drills are practiced, escapees may not only prejudice their own chances of escape but may also impede the progress of others (also see section 8.2. High Altitude Mission Support) (Davis et al., 2008; Ernsting et al.,1999).

7.6.8. Parachutes and Associated Equipment

The design of the parachute harness varies according to its use. Some harnesses are installed as part of the seat, some are fitted as part of the aircrew clothing, and some are a separate bailout system worn throughout the flight or only during an emergency. The actual designs vary, but they all have similar elements. The harnesses are made from webbing straps, usually nylon approximately 50 mm wide, which spread the load. The straps are routed to support the wearer comfortably beneath a deployed parachute with a sling passing under the buttocks and around the top of the thighs. Vertical loops pass up the back and over the shoulders to a central fitting. Some degree of lateral restraint is necessary. The harness is extended upwards from the shoulders to suspension strops, which connect to the parachute. Four of these are usually fitted to each harness, two each side of the body (Ernsting et al., 1999).

Parachutes must be fitted correctly, deploy appropriately, and have the function of steering built into the risers for most effective injury reduction. Without steering lines, parachutes are difficult to maneuver. Steerable parachutes allow aircrew to avoid obstacles in the descent path. There have been a number of ejections where aircrew had been unable to or did not attempt to steer their parachute and as a result sustained lower limb fractures. Well-designed equipment, adequate time during an emergency to deploy survival equipment, and the appropriate training to effectively and safely use the equipment are essential to preventing injury during emergency egress. Mishap investigations and data analysis have led to tremendous advances in design modifications and improvements in equipment performance, aircrew procedures, and industry standards aimed at reducing injuries and increasing survivability during egress.

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7.7. Laser Awareness Training

California: Man Gets Prison for Aiming Laser at Planes. Tuesday, November 03, 2009 from the Associated Press.

> LOS ANGELES. A Southern California man who aimed a laser beam at two airliners as they approached an airport has been sentenced to 2 1/2 years in federal prison for disrupting the flights. The U.S. Attorney's Office in Los Angeles says Dana Christian Welch of Orange, who was sentenced Monday, was the first person in the U.S. to be convicted at trial of interfering with pilots by aiming lasers at their planes. Authorities say the 37-year-old aimed a handheld laser at two Boeing jets as the passenger planes were about to land at John Wayne Airport on the night of May 21, 2008. The laser beam struck one pilot in the eye, causing "flash blindness," and interfered with pilots' ability to land the other plane.

The following information consists of excerpts from a 2008 ACC/A8D briefing.

The advent of laser technology into the weapons arena, whether for harassment, injury, mission degradation, aircraft/missile damage, or lethality, has created the need for understanding the threat and protective measures that aircrew must understand to ensure mission effectiveness and survival.

7.7.1. Background

The word "laser" is an acronym for light amplification by the stimulated emission of radiation.

Training should provide aircrew with the knowledge necessary to confidently operate in a laser environment. It is intended to:

- Describe the laser threats and hazards posed by lasers
- Define characteristics of lasers and their effects
- Provide solutions on how to deal with the laser environment

High-energy lasers are capable of destroying material, whereas low-energy lasers can jam or damage eyes and sensors. The cost of harmful lasers is decreasing, especially in the green wavelength lasers. The number of green incidents exceeds all others. The importance of the emerging technology of laser weapons and protection stimulated creation of the Directed Energy Task Force with emphasis on protection of airmen and sensors. Commercial and military aircrew are regularly reporting laser exposure incidents, and a recent case at Flight Level 270 caused temporary flash blindness. Although several aircrew were grounded and sent to an ophthalmologist for evaluation over the past year, they have since returned to flying status.

The technology is available to counter these dazzling or lethal systems with aircrew laser eye protection and sensor protection filters and limiters. Laser effects can affect the way operators and intelligence respond; hence, they affect the battle plan, which is significant.

7.7.2. Basics

Simplistically, a laser has three component parts: (1) an exciter or pump, (2) an active medium, and (3) an optical cavity. The exciter, or pump, is the component that stimulates the medium to initiate laser action. The laser medium can be a gas, liquid, or solid and is the material from which the laser energy is generated. Lasers are named by the material the medium is made from (i.e., a neodymium laser has a medium that is made from neodymium glass or ceramic, while a helium-neon laser has a medium made from helium and neon gases). The optical cavity uses special mirrors to focus the light energy in the laser on the medium and amplify or produce more intense light. The optical cavity is also used to aim the majority of photons in a specific plane or direction within the medium and give them coherence.

It takes a lot of electrical power to generate laser energy. The sinusoidal waves of laser light are all in phase (coherent). In other words, the peaks of the light waves line up. This produces light that is much brighter than normal because the amplitudes of coherent light are effectively added together. Lasers produce light that does not spread out in all directions or diverge like normal white light sources (Fig. 7.7.2-1). If a laser puts out a given amount of energy, the initial beam diameter can be used to calculate the down-range energy density.

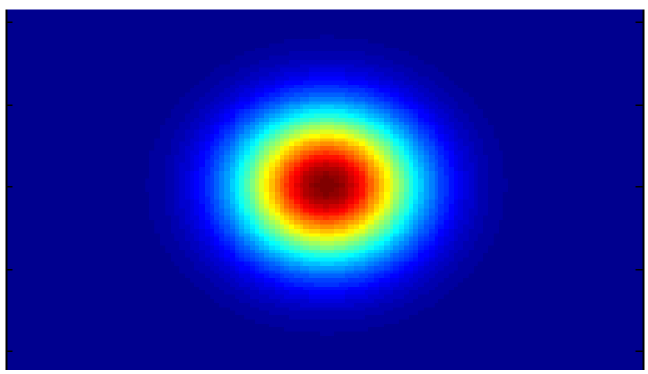


Figure 7.7.2-1. Actual Laser Beam Showing High Intensity at the Center and Energy Dropoff Toward the Edge

The down-range beam spot size is determined by the beam divergence. Less beam divergence means the beam's energy is able to travel further through space. Decreasing the beam divergence of a laser system is one way to increase its range and hazard distance.

A green laser is in the heart of the visible spectrum, where it receives the maximum magnification when passing through the cornea of the eye. The green laser light also falls very close to the wavelength of some cockpit visual displays, which creates a problem when trying to block harmful laser light but allow the cockpit display light to come through a protective shield. The wavelength that a laser is emitting is a key factor in analyzing the hazards and physical properties of the laser. There is an inverse relationship between wavelength and frequency. Shorter wavelengths have higher frequencies, while longer wavelengths have lower frequencies. Higher frequencies are associated with higher energy. As a rule of thumb, if all other parameters of a given laser are equal, a shorter wavelength will have higher energy and

will be more dangerous to human tissue. A laser beam is a vehicle used to transfer energy from the laser source and deposit it on a surface such as the eye.

Laser systems that can produce uninterrupted laser energy are called continuous wave lasers. As long as they are turned on, a beam of laser light is emitted. Pulsed laser systems emit a beam that is less than .25 s in duration. A .25-s demarcation between continuous wave lasers and pulsed lasers is based on the approximate time for a human reflex (blink) to respond to a very intense light. The total energy of a pulsed laser is compacted into a shorter time interval than a continuous wave laser, so the peak energy output is very high. This makes shorter pulses in a pulsed laser more hazardous.

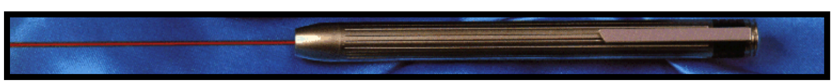
7.7.3. Laser Classes

Lasers are grouped in four basic levels called <u>laser classes</u>. Each increasing level represents an increase in the hazards associated with that class of laser because the power or energy outputs are higher from one class of lasers to the next. Class 1 lasers represent the least risk to personnel because their output is so low. Class 4 lasers are the most dangerous.

- Class 1: Any lasers that are safe under reasonably foreseeable conditions of operation; less than 8 hr continuous exposure

- Class 2: CW lasers emitting visible radiation in the wavelength range from 400 nm to 700 nm. Eye protection is normally afforded by aversion responses including the blink reflex, which is 0.25 s.

- Class 3A: Lasers that are safe for viewing with the unaided eye. For lasers emitting in the wavelength range from 400 nm to 700 nm, protection is afforded by aversion responses including the blink reflex. Direct intrabeam viewing of 3A lasers with optical aids (e.g., binoculars, telescopes, microscopes) may be hazardous. These lasers are less than five times the output of Class 1 or Class 2 lasers. Most diode pointers are 3A. Watch for danger lLabels! If it has one, don't look down the barrel.



- Class 3B: Lasers that emit an excess of Class 3A power. Direct intrabeam viewing of these lasers is always hazardous. These lasers must carry danger labels. Viewing diffuse reflections is normally safe. The Air Commanders Pointer is a Class 3B.

- Class 4: Lasers that are also capable of producing hazardous diffuse reflections. They may cause skin injuries and could also constitute a fire hazard.

- The LP-1000 laser pointer and litening targeting pod (which has a Class 4 target designator) are shown at right.

7.7.4. Laser Uses

Lasers are being used extensively for target identification and designation, range finding, and weapons guidance. The battlespace of tomorrow will use lasers in more and different functions such as combined directed energy and kinetic integrated air defense systems and force protection systems.

A laser threat is any laser light that could alter operations without causing catastrophic structural damage to platforms. Lasers represent a great source intensity, they can be hundreds of times "brighter" than the sun, the high intensity can be projected over long distances, and they are an INCREASED HAZARD! LIGHT CAN BE SHARPLY FOCUSED BY THE EYE! Lasers are dangerous because light striking the cornea is magnified 100,000 times at the fovea by the lens. See section 1.4 for the anatomy of the eye.

The region of the spectrum composed of wavelengths shorter than visible light is the ultraviolet region, and the region composed of wavelengths longer than visible light is the infrared region. In the ultraviolet region, the action is primarily photochemical, and its radiation is absorbed during the conversion from light into chemical energy, which, in turn, may damage tissue. In the infrared region, the action is primarily thermal. In the visible region, both effects are present. The cornea, lens, and retina may be affected by several wavelengths of laser light. The damage from laser radiation may range from relatively mild, from which there is complete recovery, to severe, where there is little, if any, recovery. The acute exposure symptoms include redness, tearing, conjuctival discharge, corneal surface exfoliation, and stromal haze and are extremely uncomfortable.

Invisible, near infrared wavelengths are absorbed by the retina. The human visual cells are not stimulated by those wavelengths; hence, they pose a greater threat to the fovea and retina because the aversion response (blinking) will not limit exposure. The damage potential is increased because exposure will only be sensed when actual damage occurs in the fovea. Peripheral damage may not even be noticed until extensive injury has occurred.

7.7.5. Protection

Wavelength and optical density (OD) are the two most critical factors in determining what laser eye protection (LEP) should be used in a particular laser threat environment. Most LEP devices are developed and manufactured for a specified set of wavelengths so they are considered wavelength specific. Optical density is a measure of the amount of light transmitted by a filter, such as eye protection spectacles. This term is defined such that high OD equates to low transmission of light. The OD is critical because it specifies how much of a certain wavelength's energy is blocked (reduced), thus the degree of protection. The OD, or protection factor of the LEP, is

designed to bring the energy level to below the maximum permissible exposure. The range from the laser, the magnification of optics being used, and the energy density of the laser are used to calculate OD for unique situations. The scale is exponential such that an OD of 0 equates to 100% transmission and a reduction factor of 1, an OD of 1 equates to 10% transmission and a reduction factor of 10, an OD of 2 equates to 1% transmission and a reduction factor of 100, etc. Sunglasses have an OD of about 1.

Many LEP devices resemble dark glasses with various degrees of wraparound for added protection. A problem with most LEP devices is reduced transmission with increased OD with increased protection.

Due to lack of laser detection equipment that could collect and characterize laser exposures, all exposure data currently come from the eyes of the persons being exposed. This is not good for several reasons:

- It is inherently dangerous.
- The eye cannot measure the amount of energy being received (radiant exposure).
- The brightness of the exposure makes judging the distance and color of the source difficult.
- The data are subjective.

Despite these facts, it is still very helpful if all exposures are reported promptly and as accurately as possible. It still benefits those who may be following the same flight path as the exposed aircraft by alerting others to the need to use eye protection.

Current DoD policy (17 Jan 1997) "…prohibits the use of lasers specifically designed to cause permanent blindness of un-enhanced vision…". Although it is a violation of international law to use weapons that are specifically designed to blind, such violations could occur in the future.

7.7.6. Summary

Lasers impact mission success.
Power and wavelength threats are increasing.
Protection is available at Life Support.

Report all incidents with the following information:

Location of the source?

Appearance: color, brightness?

Scanning or tracking?

Effects: mission impact, NVG?

Regularity: continuous or flashing?

References

ACC Laser Awareness Training. ACC/A8D. 2008 (Powerpoint Briefing).

Threats:

http://www.naic.wrightpatterson.af.smil.mil/Documents/HANDBOOK/SXX00097/HTML/usthreat_pagetable.shtml

Incidents: http:\www.naic.wrightpatterson.af.smil.mil/DEW/LE/index.html

General:

AFOSH STD 48-139

ANSI Z136.1 – 2007

AFI 11- 403 Aerospace Physiological Training

AFI 14-105 ACC Sup 1 Unit Intelligence Mission, Roles

AFI 11-202 Aircrew Training

AFI 11-301, Aircrew Laser Eye Protection (ALEP)

DETF: http://www.a3a5.hq.af.smil.mil/a3r/a5re/docs/directedenergy.html

Training Material: LITE CD downloadable at: http://www.acc.af.smil.mil/xr/A8D/htm

Laser Injury Guidebook

Recommended Readings

Belland KM. Aircrew performance cutting-edge tech: Emerging human performance enhancement technology vision in support of operational military aviation strategy. Chapter 5. AU/AWC/CSAT/2001-12. 1Apr2002.

Concepts

Laser eye protection (LEP)

Vocabulary

Laser

Laser classes

Optical density

8. AEROSPACE PHYSIOLOGIST ACTIVITIES

8.1. Education Theory and Practice

Lt Col Andrew D. Woodrow, USAF, BSC

8.1.1. Aerospace Physiology and Human Factors Education

The practice of aerospace physiology and human factors targets human performance and mitigation of error. The means most often employed is education of the operator; whether you are lecturing a topic in physiology for a group of undergraduate student pilots or developing a strategy for sleep-rest schedules for maintainers at a deployed location, the success of the program is linked to an understanding of learning theory and teaching practices.

In a work setting, there is an inordinate amount of training that takes place. Much of the "training" we receive is delivered with the goal to stay current in familiar topics or learn a new skill. For instance, safety issues are popular to include during unit training sessions, such as use of examples of workplace hazards and means for dealing with dangerous situations. Through it all, rules and procedures will never cover novel circumstances not covered during the instruction period. The expectation is that the learner will take the basic information and apply general rules to a broader set of scenarios. Table 8.1.1-1 provides a comparison between training and instruction and exemplifies the major outcomes of both.

Table 8.1.1-1. Key Differences Between Training and Instruction

Training allows you to…	Instruction allows you to…
Reproduce exactly what has been taught	Generalize beyond what has been taught
Act automatically	Act thoughtfully
Apply learning without variation, regardless of conditions	Adapt learning to each new set of conditions

Adapted from Stolovitch, HD in "Telling ain't Training"

To balance the work of the physiologist in practice, there is an element of education that must be considered when approaching a lesson. The term "education" implies a longer term effort derived from life experiences and highly generalized learning principles. The result of the education process is usually measured in mental models and value systems. For instance, one can receive a computer-based training (CBT) segment on the importance of oxygen at altitude that includes oxygen tensions at various altitudes and aircraft-mounted equipment used to provide adequate oxygen. If the lesson ended with the CBT, the aviator may have enough information to defend against hypoxia at altitude. However, if the learning process continued with exposure to a simulated altitude to the extent that the student experiences personal symptoms of hypoxia and undergoes a performance-based measure of recovery with oxygen equipment, the lesson is reinforced. One further step in the education process occurs when the same aviator experiences the same hypoxia symptoms in flight and responds with the techniques taught and practiced during physiology training.

Learner-centered teaching is a central theme in aerospace physiology. We live in a time when technology is only as far as a keystroke on the computer. Content-based programs account for a majority of training programs that exist in work centers. The more appropriate style is to focus on the learners with specific needs, concerns, desires, fears, and characteristics. The standardized curriculum of aerospace physiology is designed to aid the instructor in tailoring an educational experience for the class. Information-based programs lead to telling and transmission—emphasis on the instructor. Student-centered programs lead to training and transformation—focus is on the learner.

Education researchers have, for decades, looked carefully at delivery techniques and outcomes of classroom experiences. One project adopted the hypothesis that stories ought to be a central feature of any strategy for helping concrete thinkers to grasp abstract and important ideas. These stories cannot serve merely to amuse or to help people concentrate; they must actually convey philosophic content. To explain what is meant by effective stories, and why they are difficult to find and construct, consider the following example of a story about a well-known philosophical figure that helps to explain abstract ideas. The illustration acts as a principle for constructing stories well suited to the needs of concrete thinkers.

Figure 8.1.1-1. René Descartes

First, while many entertaining stories can be told of the life of Descartes (Fig. 8.1.1-1), one is useful for explaining his fascination with clear and distinct ideas as a path to certain foundations for knowledge. It is the story of a mathematical dream he had as a young man, a dream of a perfect philosophy that had all the certainty of mathematics. To tell this story in the right way is effectively to convey the passion of his philosophy; it is biography and philosophy all at once. Most stories about a thinker's life are of little philosophical use, however, and this leads to the first principle: biographical stories typically do not convey much philosophic content, as useful as they are for other purposes, and thoughtful research is necessary to construct appropriate stories. In a physiology example, to understand the first exposures to the "extreme" altitudes of balloons in the 18th century, one must first understand the initial purpose of the ascent. The French inventor Coutelle first demonstrated the balloon in 1794. He found that when he was at the end of the cables, he could clearly make out details as much as 18 mi (29 km) away through his telescope. The members of the commission were so impressed that they recommended formation of an air force, the world's first, called the Compagnie d'Aeronautiers. It was established on March 29, 1794.

Across generations, inventors, scientists, and educators have tried to bridge personal theories of learning and discovery to practical application. On the surface, statements such as René Descartes' (1596-1650) "I think; therefore I am" and Henry Ford's (1863-1947) "The hardest thing in the world to do is to think, and that is why people do so little of it" appear trite and difficult to appreciate. A true teacher must do more than recite facts; he/she must build a bridge of facts and philosophies to practical application, effectively taking the step from thought to action. The best teacher is the one who can best kindle enthusiasm by a spark of electrical fire from his/her own soul. Personal experiences are, in many respects, the mortar that holds together the scientific foundation of an aerospace physiologist. Most arrive with a wealth of laboratory or

academic experience. The key to success is to harness that knowledge to practical experiences in Air Force operations.

In spite of the development of effective training aids and simulators, the device of instruction most frequently used in aerospace and operational physiology is the lecture. Many education gurus consider the lecture one of the weakest forms of educational methodology; however, the much criticized lecture method has some significant strength when properly used. For example, to stimulate interest and convey information not otherwise available to the student, it is an economical and effective instrument of teaching. A carefully planned and well-delivered lecture is a platform a good teacher can use to allow students to learn and understand much more than they would through printed media or computer-based training. But it is easy for teachers to reduce their effectiveness by poor enunciation and distracting mannerisms. Many hours of student time have been wasted because the teacher went unprepared to lecture or because the material prepared was not planned to the best interest of the group attending. Professor I.A. Richards of Harvard used this analogy: “You have no stimulation for a person whatsoever if he thinks he understands what you are saying and why you are saying it…but how wide should the gap be between what the student is offered and what he gets? There is, as it were, a piece of elastic between you and your audience; you must not snap the elastic or you have lost them. On the other hand, you must have the biggest possible tension on the elastic and thus must be pulling at them most of the time. That is the whole point of teaching.” Brilliant. If we simply provide “consumer” level information—something easily consumed from color trifolds in the waiting room—then we fail to establish that tension.

The teacher must remember that the perceptual sensory mechanisms—eyes, ears, nervous system, pressure sensors, olfactory senses—are the means through which all our learning is accomplished. Thus, contrived experiences, such as the altitude chamber, Barany chair, parachute hanging harness, and ejection trainers, become very important adjuncts to the classroom methods. In aerospace and operational physiology, videos are also a useful tool but should not be used in place of another, more effective teaching method. A constant evaluation of materials presented (e.g., video, audio, photo) must be made; nothing is more uninspiring than presenting the very same lesson plan to a student 5 yr after the last presentation. A combination of materials may do a better job than a single method, and, again, one may be more effective than another. The instructor must consider both the purpose of the material and the background and experiences of the aircrew in the class.

“What is perceived by the student is fixed in the mind more firmly than what is merely said over a hundred times. It is not the shadows of things but the things themselves that should be presented to the student” (Swett, 1880). From this observation, the instructor needs to, once again, assess the objectives of the lesson and the methods to most effectively convey the message. A well conducted class is choreography of auditory, visual and tactile input bound together with the enthusiasm for the importance of each lesson; not peppered with distractions of materials unrelated to the topic. The constant progress of excellence in teaching across the AOP spectrum is the goal. How will you meet that goal?

8.1.2. Education via Allegories

The balloon corps, or Aerostiers, transported L'Entrepremant to Mauberge, where Coutelle inflated it, and the air corps was ready to face the enemy, or at least to see the enemy. The air corps went into action against the Austrians in June 1794. During the battle, Coutelle and Conté successfully spied on Dutch and Austrian troops from high above Mauberge. They provided detailed reports of the location and composition of the Austrian and Dutch troops and directed ground fire against the forces. The Austrians protested that the use of a balloon was against the rules of war and attempted to shoot it down, but Coutelle had his ground crew let out more cable, and L'Entrepremant easily rose out of range. As balloons soared higher and higher, there were reports from occupants of strange sensations and even visual illusions. It would be some years before the connection between altitude and lack of oxygen was made.

Using stories to support a complex topic may cause the learner to make a lasting connection in the process of memory. The three categories of memory are sensory, short term, and long term. The sensory memories act as buffers for stimuli received through the senses. To best understand sensory memory, one should review the neurology of the human sensory systems. A sensory memory exists for each sensory channel: iconic memory for visual stimuli, echoic memory for aural stimuli, and haptic memory for touch. Information is passed from sensory memory into short-term memory by attention, thereby filtering the stimuli to only those that are of interest at a given time. When learning includes sensory information, such as parachute operations from a swing landing trainer, the student picks up on the verbal commands of the instructor along with the tactile input from the open shock during the initial drop from the tower.

8.1.3. Memory

<u>Short-term memory</u> is the wax tablet of memory for temporary recall of the information under process. For instance, a series of numbers related to radio frequencies or headings must be held in your mind from the beginning of the transmission to the end until it is time to act on the information. Short-term memory decays rapidly (200 ms) and also has a limited capacity (Partridge, 1993). A common term in human factors is “chunking,” wherein information is grouped for ease of storing more capacity in smaller bundles. The most common example of chunking is a hyphenated phone number, which is easier to remember than a single long number. Interference often causes disturbance in short-term memory retention. In aviation, if high-frequency radio communication is interrupted by interphone transmission, the receiver may lose some or all of the information presented. This accounts for the desire to complete the tasks held in short-term memory as soon as possible.

<u>Long-term memory</u> is intended for storage of information over a long time. Information from the working memory is transferred to it after a few seconds. Unlike working memory, there is little decay. There are two types of long-term memory: episodic memory and semantic memory. <u>Episodic memory</u> represents our memory of events and experiences in a serial form. It is from this memory that we can reconstruct the actual events that took place at a given point in our lives. When teaching a topic that is unfamiliar, it may be appropriate to first identify the backgrounds and experiences of the audience to better tailor the presentation. Semantic memory, on the other end, is a structured record of facts, concepts, and skills that we have acquired. The information

in semantic memory is derived from that in our own episodic memory, such that we can learn new facts or concepts from our experiences. Again, to understand the process of learning, the instructor must first understand the mechanics of processing new information and retrieving previously stored information.

There are three main activities related to long-term memory: storage, deletion, and retrieval. The most common analogy is the personal computer; however, instructional theory often neglects the impact of environment and motivation to learn—both are relevant and important features for accurate retrieval. Information from short-term memory is stored in long-term memory by rehearsal. The repeated exposure to a stimulus or the rehearsal of a piece of information transfers it into long-term memory.

Experiments also suggest that learning time is most effective if it is distributed over time. In a 2-day physiology course for aviators, time is not a function that can be easily manipulated. Reinforcement of basic concepts related to physiological changes in flight is the best means of distributing information over time: first in the classroom lecture, then in the oxygen equipment lab, and finally in the chamber while at altitude. Deletion of information or knowledge is mainly caused by decay and interference. Emotional factors also affect long-term memory. Most research indicates that we never really forget anything, but rather it becomes increasingly more difficult to access the memory. However, it is debatable whether we actually ever forget anything or whether it becomes increasingly difficult to access certain items from memory. The amount of information stored in any aircraft-mounted system typically exceeds the fluid memory capacity of the human brain, although the actual span of information held in the brain far exceeds any computer chip. It is simply the retrieval that may need prompting from time to time, a function of our attention and motivation to recall.

8.1.4. Retrieval

There are two types of information retrieval: recall and recognition. In recall, the information is reproduced from memory. Recall might be highlighted through the example of read-back of air traffic control (ATC) direction. All pilots are trained to recite a prescribed set of information in a prescribed order to the controller as the approach is made to the airfield; the prompt is not written but verbal from the ATC to the pilot. Association of symbols presented on a multifunction display to meaning for each symbol is an example of recognition. In recognition the presentation of the information provides the knowledge that the information has been seen before. Recognition is of lesser complexity, as the information is provided as a cue. However, the recall can be assisted by the provision of retrieval cues, which enable the subject to quickly access the information in memory.

Learning tends to increase or decrease the effectiveness of impulses that arrive at junctions between neurons. Prior to introducing new concepts, it is very helpful to the student if the instructor can make a connection between common items or preexisting knowledge. Encoding is the first of three stages in the memory process, involving processes associated with receiving or registering stimuli through one or more of the senses and modifying that information. Before an instructor can use a concept like encoding, it is appropriate to review the wiring of the neural network.

The hippocampus receives input from all cortical association areas and serves as the final processing station of complex sensory information. Moreover, it is recognized as a central structure for the functional neuroanatomy of different memory processes. The interaction between the hippocampus and adjacent structures may help in

understanding the following example: How might the association between the words "dishtowel" and "locomotive" be stored in neural network models of the hippocampus? First, recognition of the two words activates regions of the temporal lobe language cortex (Fig. 8.1.4-1). Patterns of activity then spread into populations of neurons in the entorhinal cortex. Physiological and behavioral evidence suggests that the parahippocampal and entorhinal cortices provide the means for holding information about this event for a period of time (Stern, 1997). The neurons that receive the additional information do not represent the use of the words "dishtowel" and "locomotive" in all contexts but instead represent the specific use of the words in the specific behavioral context. The same neurons will play a role in portions of a wide variety of different memories. These neurons provide the basic code for the episodic memory.

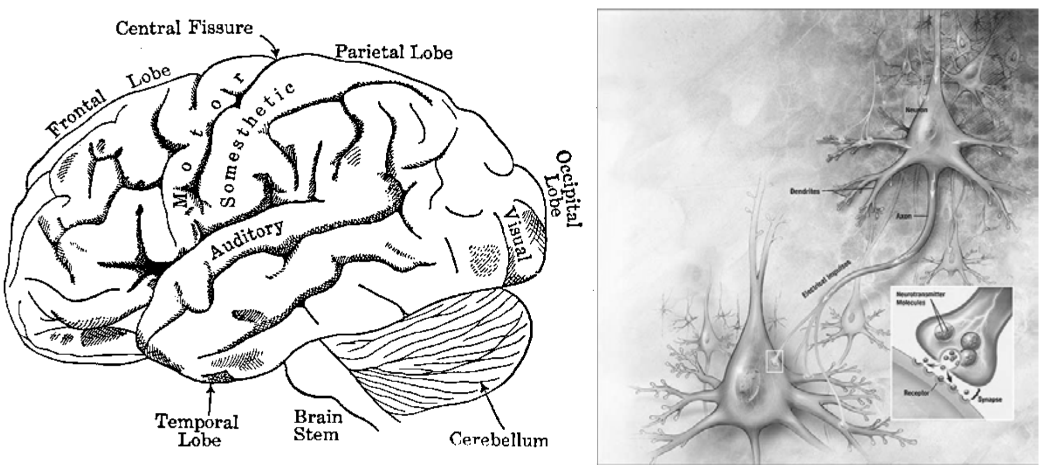


Figure 8.1.4-1 Brain Regions and Depiction of Neuron Pathway

8.1.5. Discussion

The effect of prior knowledge on learning cannot be underestimated. Adult learners come to physiology training with a unique set of prior learning sets, some with medical backgrounds, others with engineering, some with no more than high school science. If the instructor treats the learners as if they have little or no experience when they do, the instructor will lose them. It is critical to acknowledge the rich store of experience each has, and exploit it. In the aerospace physiology and human factors classroom, there should always be an objective to the lesson. The objective may be establishing a position on reducing error rates in aviation. The instructor holds the key to making the learning effective, but must understand that each student has a likely position on how to reduce error rates. How might position-driven discussions support learning human factors? This technique causes the instructor to step away from the podium and actually maneuver the discussion throughout the students. First, position-driven discussions promote active participation before students are fully competent in a domain. In many cases, everyone is expected to commit to a position (and explain why), but it's perfectly fine to build on (or even copy) someone else's reasoning, provided the student states it in his or her own words. The instructor's role is to help students clarify and make explicit their position and the evidence for that position. Taken together, this kind of group discussion provides a great deal of support for students to listen to one another, build on one another's ideas, and take on new "ways

with words" in the process. Because the goal is to have a well-developed position, which may or may not be right, students are willing to participate, even those who are most reluctant to participate in other kinds of group discussion. And each student is credited as a "player," a holder of a position or theory, whether or not his or her prediction or explanation wins out in the end. This provides a productive bridge from operational squadron level to the more academic forms of reasoning.

There are, however, some potential difficulties with this kind of group discussion talk format. First, it works most easily with science demos or cases where the question on the table has a definitive answer, one that can be demonstrated or revealed to the students after their discussion and arguments. Ideally, correctness rests in the world (as in the scientific domain), rather than with the instructor. The instructor does NOT evaluate student contributions as right or wrong, as might be more common in other kinds of instructor-guided discussion or recitation. Rather, in position-driven discussions, the instructor typically scaffolds students by "revoicing" their contributions and pushing for clarification, so that everyone has access to everyone else's reasoning (O'Connor, 1998). This a good method to use when discussing aircraft mishap investigations; everyone in the room has a vested interest in nurturing a safe approach to flight, and each crew member has a theory of how to make flight safe. Allowing open discussion and various viewpoints is more important to the learning process than nailing the "right theory" until of the end of the discussion, where, for example, the video of an accident scenario is run and students see the actual outcome. At that point, the instructor's role changes, and a focus on correctness, getting the right theory, and actively explaining to the students how to think about the situation takes place.

Secondly, coming up with good framing questions is not easy. A planned discussion requires both a well-designed task and a carefully constructed framing question that will provoke a range of reasonable positions, no one of which is obviously correct. Additionally, the question must be carefully selected and sequenced among other tasks so as to advance the thinking of the group as a whole. It is unreasonable to expect an instructor to develop framing questions for programmed discussions without the support of a rigorous, coherent curriculum that emphasizes student reasoning and inquiry through group discussion. The goal of standardized curriculum is to provide the starting point for this discussion.

A third potential difficulty is that position-driven discussions crucially involve the instructor's active role in orchestrating, eliciting, and scaffolding students' predicting and theorizing. To pull off a "position-driven discussion" so that it engenders productive theorizing and learning, an instructor has to be comfortable with the domain and should know what kinds of assumptions learners are likely to make about the lesson. In guiding the discussion, the teacher must make productive use of students' nontechnical, everyday experiences as well as their observations and experiences of the current problem. Although well-designed and well-sequenced discussions on science topics can carry a great deal of "intelligence" about the science under investigation, instructors must know the domain well to facilitate coherent and academically productive position-driven discussions.

8.1.6. Convey the Message

The methods used to convey a message and ultimately teach aircrew about aerospace physiology and human factors will vary based on the environment of your teaching platform. Whether you are in the hangar following a sortie, in front of the Wing staff during a safety day, or in a formal school house guiding through standardized curriculum, the impact you make through solid practice of educational theory is the foundation of the career field. Developing the skills to deliver a lesson that is relevant, substantive, and current is one of the most important tools to refine in your arsenal. Use the research and practice of education professionals to bridge to the communities serviced by Aerospace Physiology.

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Concepts

Computer-based training (CBT)
Information retrieval

Vocabulary

Episodic memory
Long-term memory
Short-term memory

8.2. High-Altitude Mission Support (HAMS)

Lt Col Andrew D. Woodrow, USAF, BSC, and Col Donald J. White, USAF, BSC

It's 2045 hours, flying at FL250 over hostile territory, the dimly lit cargo compartment of the MC-130 is a scene of methodical activity. A team of seven Air Force combat controllers, two pararescuemen, two physiology technicians, and the loadmaster perform pre-jump duties. The droning of four 4400 horsepower turboprop engines drowns out any other sounds in the cargo area, but the communication is practiced hand and body gestures. As the Hercules approaches the drop zone, the navigator and loadmaster make last inputs via intercom to line up the aircraft on the release point. The nine parachutists disconnect from the oxygen consoles and activate their portable oxygen systems. Chemical lights flicker into view as the jumpers crack the glowsticks taped to their helmets. Each shuffles laboriously forward with nearly 100 pounds of gear hanging from their back, chest and legs toward the large black square of darkness that was once the ramp of the Hercules. The red light beaming on the darkened fuselage is suddenly changed to green, the jumpmaster raises his hand with one final gesture and the nine jumpers step off the ramp, one by one disappearing into the darkness. As the ramp begins to close, the aircraft makes a left bank and change of course back to the airfield. The warriors have been safely delivered to the drop zone, the aircrew have completed another high altitude mission, and the physiology techs are preparing the oxygen equipment for the next sortie. It is 0245 and the crew clocks out for a well deserved crew rest period.

8.2.1. Terminology

Several terms are used when referring to missions that require support from aerospace physiologists and <u>physiological technicians (PTs)</u>:

<u>High altitude low opening (HALO)</u> is a term used to refer to all high-altitude airdrop missions that require a jumper to freefall to a lower parachute opening height. Traditionally, all high-altitude airdrop missions including leaflet drops and other cargo drops were referred to as HALO missions. More specifically, HALO procedures consist of parachutists jumping from an altitude above 5,000 ft then delaying parachute deployment until the last safe moment (approximately 2,000 ft). The purpose of HALO operations is to enable jumpers to depart inconspicuous aircraft and descend through the harsh, high-altitude environment and land with minimum exposure to enemy small arms fire. The high-altitude jump also protects the aircraft and crew from ground fire.

<u>High altitude high opening (HAHO)</u> is a term that describes parachute operations where the jumper delays deployment of the chute just 10-15 s following departure from the aircraft, then uses a high glide ratio parachute to steer to a landing zone. This procedure allows a drop zone and altitude that are well away from enemy activities. The square rigs allow parachutists to steer and glide considerable distances with minimum risk of exposure to themselves and the delivery aircraft to ground fire.

8.2.2. History of HAMS

The 15th Physiological Training Flight at Kadena Air Base, Japan, began supporting HALO parachutists in 1965. The training missions were typically staged from 13,000 ft to 35,000 ft. In 1965, the U.S. Army's 7th Psychological Operations Group tasked the 374th Tactical Airlift Wing (TAW) at Clark AB, Philippines, to provide aircraft and crews to support leaflet dropping missions in Viet Nam. The initial missions demonstrated that crewmembers involved with physically strenuous actions of leaflet dropping from unpressurized aircraft at FL250 often suffered physiological problems like hypoxia, hyperventilation, and decompression sickness. The C-130s used in the airdrop missions did not have enough oxygen stations plumbed for the crew and support teams, and the war efforts did not afford enough time to refit airframes with additional oxygen systems. In 1966, the 374th TAW requested assistance from the 15th Physiological Training Flight (PTF), and the oxygen solution was set in motion using newly designed, portable oxygen consoles. The 374th TAW/CC also requested that physiology technicians fly onboard to monitor the use of the new oxygen consoles along with the safety and well being of the crew.

In May 1971, the 15th PTF began regular support of COMMANDO VAULT missions, and in April of 1972, the PTF assumed physiological support of the container delivery system missions in Southeast Asia. Initial support was by temporary rotations from a detachment at Cam Rahn Bay and Tan Son Nhut, Republic of Viet Nam. In the period from 1966 to June of 1972, over 2087 missions were flown with PTs on board. The importance of PT support on these missions was summed up by Brig Gen Kelton Farris, the 374th TAW Commander, when he said, "The utilization of personnel with years of experience in coping with similar problems experienced in physiological training proved to be a determining factor for mission success. The cases of decompression sickness, hyperventilation, and hypoxia encountered on initial missions were markedly reduced…their quick, expert, and initial treatment has safeguarded the well being of personnel and frequently corrected the difficulties encountered, prevented the abort of missions…we do not fly these missions without physiological training personnel." Each of the PTs involved with airdrop missions was on flying status and received hostile fire pay, and many received Air Medals for support of the missions.

Aerospace Physiology Training Units (APTUs). APTUs in CONUS were involved in HALO support missions starting in 1967. At the time, Tactical Air Command (TAC) was conducting special physiological training for aircrew and jumpers who performed missions above FL180. The training initially consisted of a modified passenger course to cover areas of concern when flying above 18,000 ft. In Europe, high-altitude airdrop mission support (HAAMS) physiological support requirements began in 1981. The APTU at Wiesbaden Air Base, West Germany, received five nonrated aircrew positions that were designated for HAAMS support. In 1977, the Military Airlift Command (MAC) Coordinator for Aerospace Physiology became the program manager for world-wide HAAMS support. In 1982, HALO became only part of the HAAMS requirement. HAAMS is the term that replaced HALO as a universal term for airdrop mission support. Most recently, in 2006, the term shifted again to high-altitude mssion support (HAMS) to reflect a more universal use of PTs to support crew as well as jumpers. Since much of the information on HAMS was written using the previous acronym, HAAMS, they are used interchangeably in this document. Several conferences were held through the 1980s to better refine the program, and in 1987, Air Force Regulation 50-27 formally designated the MAC Coordinator as the central point of contact for assigning missions

to PTs. By 1988, there were eight functional APTUs designated across the MAJCOMs to provide HAAMS teams. The majority of qualified team members were 911X0/4MO with a few 916X/43A3 officers to assist.

In 1995, PTs flew 550 sorties aboard aircraft, including the C-17, C-130, C-141, C-5, and others. They launched from 114 locales, including Pakistan, Australia, Indonesia, Korea, Italy, and airfields throughout the United States. Because of the high demand for qualified PTs, the 1st AS is augmented by aerospace PT units at Shaw AFB, SC; Little Rock AFB, AR.; Andrews AFB, MD; Fairchild AFB, WA; Edwards AFB, CA; and Kadena Air Base, Japan.

In 2006, the School of Aerospace Medicine established a formal training course for newly assigned PTs to HAAMS Unit Type Codes (UTCs). Each team member must maintain currency in physiological training and medical clearance to fly, plus complete a series of training sorties and be proficient in emergency egress procedures for each platform flown.

8.2.3. The Mission

A large number of manned high-altitude jumps are HAHO and equipment drops, along with decades of experience in equipment trials at the parachute freefall school and test parachute center. HAMS for special assignment airlift missions, often top secret and clandestine affairs, carry elite troops from every branch of the service—Army Rangers and special forces, Marine recon forces, Navy SEAL teams, and Air Force special tactics units. Jumpers from all services parachute at altitudes up to 35,000 ft with all of the accompanying hazards. High glide ratio parachutes utilize HALO and HAHO techniques during day and night operations and under all weather conditions.

The Joint Airborne/Air-Transportability Tactical Training planning meeting will project requirements for high-altitude mission support. Once identified, the requirement is coordinated through various channels including the physiological support representative at Air Mobility Command (AMC). The request for support is forwarded through the PT community, and the designated HAMS team then contacts the user group (USAF, Army Special Forces, Navy SEAL Team, etc.) to coordinate special requirements and mission details. Once in place, the HAMS team will set up oxygen equipment and support equipment and prepare for the lift. Close coordination with the aircraft loadmaster is essential to the PT for proper placement of the oxygen equipment and onboard support. When the crew is assembled for mission brief, the PT will conduct a short physiological hazard brief and review emergency procedures in the event of a physiological reaction in flight. The PT also provides a physiological brief to the jump team prior to boarding the aircraft.

Throughout the flight, the PT monitors the jumpers for hyperventilation, oxygen discipline, and any other physiological reactions. The role on board an aircraft is very similar to that of an inside observer in the altitude chamber. If an airdrop is planned above FL180, the PT must coordinate with the crew to ensure the jumpers and crew complete the requisite prebreathing prior to the 6-min warning preceding aircraft depressurization. Part of the PT's job is to carefully record the start time of prebreathing, the take-off time, and the time the cabin crosses through critical altitudes like 10,000 ft, FL180, and FL250. The PT notifies the crew of any physiological reactions during flight. Once the jumpers have disconnected from the console oxygen, the PT checks each console, stows the extension hoses, and assists the loadmaster with equipment storage.

8.2.4. Role of the PT

The role of the PT is to provide an experienced eye for identification and response to physiological emergencies due to exposure to high altitude. While on board, the PT is a critical part to ensuring a safe and successful mission. The wartime task of high-altitude mission support is a niche that is specially suited to the physiology technician.

HALO techniques are used for missions to prevent detection of the aircraft and the jumpers. Extreme accuracy is required since the parachutes are deployed at a low altitude. HALO involves paratroopers jumping at around 25,000 ft and freefalling down to 3,500 ft. Plummeting at a terminal velocity of 126 mph, parachutists can descend this distance within 2 min. A HALO jump gets jumpers out of sight in a hurry, and they are less vulnerable to dangers. A drawback to this technique is that the jumpers must exit the aircraft over, or close to, enemy territory, thus making the aircraft a potential target for enemy surface-to-air or air-to-air defenses.

HAHO techniques are used for missions that require minimal detection of the aircraft under conditions that restrict the aircraft from penetrating a certain area, such as the border of a country. The jumpers will deploy the parachutes at very high altitudes, which allows them to glide a considerable horizontal distance with a low probability of detection. Jumpers are consequently exposed to hypoxia and cold temperatures for extended periods. A HAHO is a high-altitude, high-opening jump used for long-range insertion. During high-altitude, high-opening missions, both exit and deployment altitudes are high, and a special parachute lets them maneuver more than 50 km as they quietly float into an area. HAHO allows the jump aircraft to deliver its cargo from a significant standoff range, thereby reducing the odds of enemy detection and increasing the survivability of the aircraft and the parachutists. The higher the parachute-opening altitude and the flatter the glide slope of the parachute, the greater the standoff distance attainable. Paratroopers “hop and pop” their chutes immediately, which is potentially a riskier maneuver because jumpers are exposed to altitude and the enemy for a longer period. The opening shock is also traumatic. It gives quite a jolt. Jumpers are sore for a few days after a HAHO.

Given the same size parachutes, a heavier parachutist will descend more rapidly than a lighter one. This variable rate of descent is not a problem in low-altitude airborne work; military parachutists traditionally carry their individual combat gear with little regard for weight considerations. However, that approach doesn’t work in HAHO operations. Because a HAHO team may travel more than 40 mi under their canopies, a common rate of descent is a critical factor in keeping the team together. To ensure the glide slopes are as uniform as possible, the team’s gear is carefully apportioned so that all the team members weigh about the same – heavier troops jump with lighter equipment containers and lighter troops jump with heavier containers. The team’s equipment can be redistributed into operational loads after landing.

The most hectic time is from the 2-min warning until the jump. The team is switching over to their oxygen bottles, and you're double- and triple-checking equipment, connections, and bottle pressure and watching for symptoms and signs of hypoxia.

8.2.5. Hazard vs. Safety

The two greatest hazards they must contend with on HAAMS are hypoxia and decompression sickness. Hypoxia is a major concern during both techniques; there is one documented fatality associated with a high-altitude jump. To compensate for the body's craving for oxygen, the heart and breathing rate increases. Hypoxia affects people uniquely, and its symptoms will change with age and lifestyle. That's why all aircrew members are required to go through the altitude chamber periodically. At 10,000 ft, subtle changes take place in the body, and these multiply as you go higher. At 35,000 ft, you'll have between 30 to 60 s of useful consciousness without supplemental oxygen. Ultimately, this leads to death.

Special Operations Forces regulations define the requirements for safe operation and mission completion. For day operations, supplemental oxygen must be used by all parachutists above 10,000 ft mean seal level (MSL) in the aircraft if exposure exceeds 30 min. Oxygen is supplied either by inline oxygen or from portable cylinders. If there are extremes in temperature or physical exertion, the jumpmaster can recommend supplemental oxygen at 5,000 ft MSL. Supplemental oxygen is used during the parachute descent for any jump above 13,000 ft MSL and can be an option for jumps initiating below 13,000 ft MSL. For night operations, supplemental oxygen is required in the aircraft for all parachutists above 10,000 ft MSL while flying to the drop zone and is encouraged for altitudes above 5,000 ft MSL at the discretion of the jumpmaster. HALO operations may be performed below 13,000 ft MSL once the parachutist has left the aircraft. HAHO operations above 10,000 ft MSL must be performed with supplemental oxygen both in the aircraft and under the parachute canopy. Aircraft oxygen delivery systems must be capable of delivering 100% oxygen and supplemental oxygen settings with a mask that conforms to physiologic PRICE check procedures. Parachute canopy oxygen delivery systems such as a simple oxygen cylinder and mask must maintain the jumper's oxygen hemoglobin saturation greater than 92%.

The cold is another factor jumpers must contend with. For every 1,000 ft you ascend, you lose 3.6 °F in temperature. In those conditions, knowing the wind-chill factor (a function of ambient temperature and wind speed) is important. A parachutist must have manual dexterity for a few minutes before exiting the aircraft to properly adjust the equipment and immediately after exiting to manipulate the parachute. The parachutist's hands would become extremely cold unless over-gloves are pulled on.

Any time a military flight drops personnel or cargo at altitudes above 18,000 ft, specially trained aerospace physiology technicians, nicknamed PTs, must fly on board. These technicians, who are experts in the field of human performance and the effects of flight on the body, monitor the aircrew and parachutists, looking for signs of impairment caused by altitude. A physiology tech's most critical duty is recognizing and treating those taken ill by the altitude. They administer to the sick until relieved by a flight surgeon.

PTs work hand-in-hand with the aircraft commander and jumpmaster. They brief aircrews and parachutists on the hazards of high-altitude operations and act as an in-flight oxygen equipment and physiological consultant. Physiology technicians also repair the oxygen equipment, which includes prebreathing consoles and oxygen bottles strapped to the paratroopers. All receive training from equipment manufacturers so they can troubleshoot and repair malfunctions on the spot.

They regulate the ascent to altitude, directing all on board to "prebreathe" 100% oxygen from a console for a half hour while holding the aircraft below 10,000 ft. This

interval isn't to catch a breather but to purge nitrogen from the bloodstream, eliminating 90% of the cases of decompression sickness. The squadron's aerospace physiology techs, who average 6 to 7 yr worth of experience, know the pressure-volume law of gases (Boyle's Law) inside and out. It states that PV=k. Pressure and volume are inversely proportional so that when you decrease pressure, volume increases.

Concepts

Physiological technicians (PTs)
Role of the PT

Vocabulary

Aerospace Physiology Training Units (APTU)
High altitude high opening (HAHO)
High altitude low opening (HALO)

8.3. High-Altitude Reconnaissance Mission Support (HARMS)

Lt Col Andrew D. Woodrow, USAF, BSC

1933	First full-pressure suit--English firm for American balloonist Mr. Mark Ridge--Suit taken to 17 torr (84,000 ft) pressurized to 36,500 ft (Sears, 1995).
1934	Wiley Post Suit--B.F. Goodrich, full-pressure suit of double-ply rubberized parachute fabric, pigskin gloves, rubber boots, aluminum helmet pressurized to 7 psi, 10 flights before Post's death in 1935 (Sears, 1995).
1943-46	Henry et al., at the University of Southern California, designed the capstan partial-pressure suit and exposed subjects to 80,000 ft--3 models (Sears, 1995).
1960-70s	S901/970--A-12, YF-12A, and SR-71 full-pressure suit with integrated subsystems, parachute harness, automatic flotation system, urine collection device, redundant pressure control and breathing system, thermal protective garment, custom plus 12 sizes, various models; David Clark Company (Sears, 1995).
1960-70s	SlO10--Special projects full-pressure suit with integrated subsystems including parachute harness, automatic flotation, redundant pressure control and breathing system, thermal protective garment, custom plus 12 sizes, various models used in U2-R; David Clark Company (Sears, 1995).
1970-80s	S1030--Upgraded SR-7l full-pressure suit, link net with integrated subsystems; David Clark Company (Sears, 1995).
1982	TLSS/ALSS--Tactical Life Support System. Developed by the USAF and Boeing/Gentex et al. to provide get-me-down protection from 60,000 ft. Incorporated many new features for a modular mask, vest anti-G suit ensemble integrated to provide PBG for high-G maneuvers and PBA for altitude with G trousers providing 4 times the breathing pressure from a molecular sieve oxygen concentration system. There are now many variants of similar protective design in the United Kingdom, Canada, Sweden, and an Advanced Oxygen System from France (Sears, 1995).
1987-89	AHAFS--Advanced High-Altitude Flight Suit. High pressure (5-6 psi) full-pressure suit developed for the USAF to increase mobility at higher operating pressures; ILC Dover (Sears, 1995).
1993-94	Partial-pressure suit developed for F-22 aircraft. Get-me-down partial-pressure ensemble combining mask/vest/uniform pressure anti-G garment for protection to 60,000 ft. USAF contractors include Boeing, ILC Dover, META, and Helmets Ltd. (Sears, 1995).

One of the two primary wartime skills supported by aerospace physiology is the High-Altitude Reconnaissance Mission Support (HARMS) program. This function is a highly specialized hybrid of life support and physiology and consists of survival continuation training, full-pressure suit maintenance, survival kit and parachute maintenance, high-altitude chamber flight training, and integration of the pilot to the cockpit. The program has been operating for over 52 yr in support of various aircraft including the SR-71, WB-57, TR-1, and U-2. Along with daily worldwide flight operation support, the 9th Physiological Support Squadron (PSPTS) at Beale AFB, California, is the USAF Full-Pressure Suit Depot. As such, the depot is the single point of

configuration control, maintenance, and procurement of all life support equipment assigned to the U-2. Additionally, all personnel assigned to the 9th PSPTS undergo a 10-mo specialized training and certification program through each facet of the operation.

8.3.1. The Platform

Since the original design in 1955, the U-2 (Fig. 8.3.1-1) has been a stalwart of the intelligence, surveillance, and reconnaissance (ISR) inventory. The aircraft carries highly sophisticated sensors capable of wide sweeps of terrain; outside of reconnaissance this has proven useful in mapping forest fires and during rescue missions at sea. A single-seat, single-engine reconnaissance aircraft capable of altitudes in excess of 70,000 ft, the platform presents one of the most challenging human integration environments in the Air Force. The cabin pressure is normally no higher than 29,000 ft, but the cruising altitude requires the pilot to wear a full-pressure suit in the event of decompression. Loitering time is one of the biggest advantages to the 108-ft wing span: no aerial refueling yet the aircraft can sustain missions of over 10 hr. The aircraft is fitted with a Lockheed-Martin ejection system capable of safe ejection at maximum altitude.

Figure 8.3.1-1. U-2 High-Altitude Reconnaissance Aircraft

8.3.2. The Support Team

Composed primarily of physiology (4M0) and life support (1P1) technicians and supported by aerospace physiologists (43A3), the “PSD tech” has considerably different responsibilities from normal duties in a physiology unit or life support shop. A short summary of the primary responsibilities follows:

Depot level maintenance. Repair, overhaul, and inspection of full-pressure suits (FPS) and associated hardware are accomplished at Beale. This includes oxygen regulators, anti-suffocation devices, pressure suit controllers, helmet components, gloves, FPS bladders, urine collection devices and valves, to name a few.

Periodic and preflight inspections. Parachutes, survival kits, and FPS assemblies are inspected, to include integration of the equipment to the aircraft. Also, the pilot preflight health survey, assessment of pilot’s basic physiologic condition, and preflight eating and sleeping habit surveys are completed.

Integration to the cockpit. Installation and removal of the parachute and survival kit are completed, and the pilot is integrated with the aircraft. All necessary oxygen

systems, ventilation systems, communication systems, and egress systems are correctly connected prior to launch.

Specialized pilot training. High-altitude chamber flights to FL700 are conducted as part of formal physiological training and as a fit and function check of the suit and related components.

8.3.3. The Mission Sequence

All PSPTS flight support operations include preflight, launch, and recovery elements. Pilots assigned to fly a mission are assisted by a mobile safety officer ("mobile"), who acts as the back-up pilot on mission day. The PSPTS technicians will prepare suits for both pilots if the mission is a high priority. The day prior to the mission, the FPS and associated components undergo preflight inspections. On the day of the sortie, the aircraft is loaded with inspected parachute and survival kits approximately 2 hr prior to launch. As part of the cockpit preparation, oxygen systems, ventilation systems, and intercom are checked. Prior to FPS donning, the pilot completes a health screening with one of the PSPTS technicians; this will include blood pressure, temperature, 12-hr history of eating, and 24-hr sleep history. Approximately 1.5 hr prior to launch, the pilot dons the FPS; this requires two technicians and a supervisor to complete all integration checks. One hour prior to launch, the pilot begins a denitrogenation period with optional exercise enhancement. At this point, the FPS is fully integrated with helmet in place and 100% oxygen delivered through the helmet regulator. Additional details about each component are described below.

While the mission pilot is prebreathing oxygen, the mobile is completing aircraft checks and configuring the cockpit for the mission pilot. This task sharing prevents excessive workload on the mission pilot while in the FPS. The mission pilot is transported to the aircraft in a specially designed step van by the three PSPTS technicians. Cooling air is provided to the FPS via a series of vent ducts integrated to the suit; the cooling air is delivered through a liquid oxygen converter. The cockpit integration is completed by the technicians and checked by the supervisor prior to canopy closure. The PSPTS technician removes the safety pins from the parachute, ejection D-ring, and canopy jettison T-handle prior to canopy closure.

The process is reversed during the recovery phase. The PSPTS technicians debrief the mission pilot on any physiological issues encountered during flight and then complete postflight inspections on all equipment.

8.3.4. The Equipment

A short description of the key components required to support the high-altitude reconnaissance mission is crucial to understanding the complexity of the operation. Each component undergoes thorough inspection prior to and following every mission. Since the approval of assignment of women to combat aircraft in 1989, the U-2 equipment inventory has gone through a few modifications to better serve both genders; however, the principles of physiological support remain the same.

8.3.4.1 Pressure Suits. The protection given by oxygen regulators and oxygen masks is sufficient for the operational and emergency altitudes established for the various types of oxygen delivery systems. The limiting factor for sustained flight at, and above, FL500 is primarily an individual's respiratory and circulatory physiology rather

than technology to develop oxygen regulators and masks. As the flight altitude is extended beyond FL430, the necessity for breathing 100% oxygen at increasingly higher pressures becomes critical. The flyer cannot tolerate the elevated breathing pressures for an extended period of time because the normal function of respiration and circulation becomes seriously impaired (Fig. 8.3.4-1).

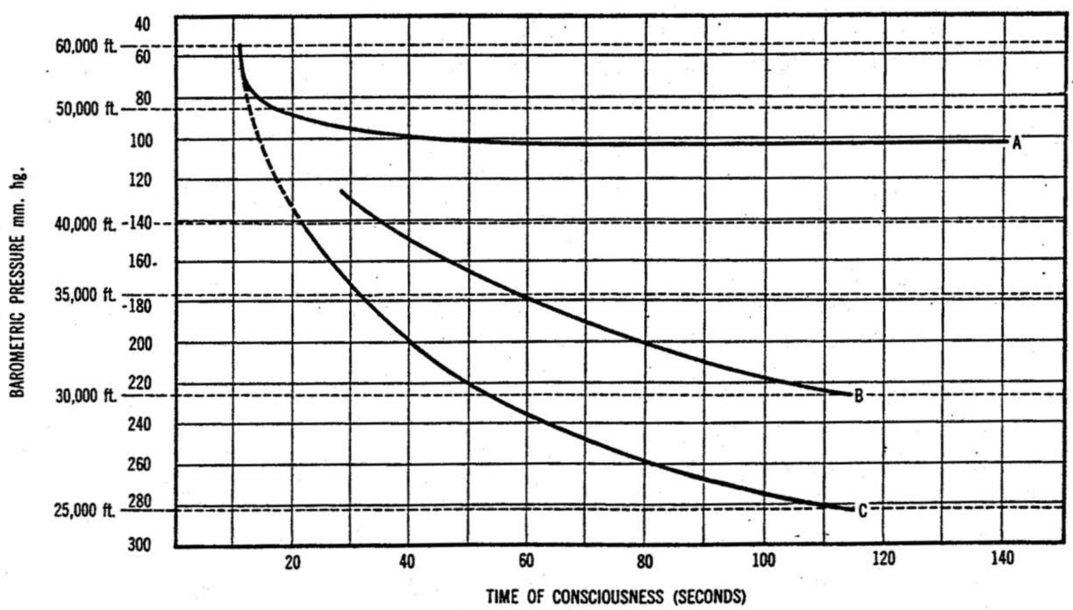

Figure 8.3.4-1. Effective Performance Time of Consciousness with Varying Types of Exposure at High Altitude
A. EPT after rapid decompression on oxygen
B. EPT after turning off oxygen at altitude
C. EPT after rapid decompression on air

The need for pressure suits arises primarily because of the hypoxia threat. A plane may ascend to an altitude above FL500, and the aircrew needs backup protection for the pressurization system. Sustained flight of the U-2 at very high altitudes results in an excessively high cabin altitude because of limitations in pressure ratio and compression temperature.

8.3.4.2 Design Criteria. Pressure suits are designed to embody three primary considerations: protection, mobility, and comfort. The basic protection provided by a pressure suit is the prevention of hypoxia. High breathing pressures can be tolerated in a pressure suit because of the counterbalance effect of the pressure suit and helmet. Counterpressure may be achieved by using a pressure suit that applies a mechanical squeeze force on the flyer's body or by surrounding the body with a pressurized gas envelope.

Some pressure suits are specially designed to guard against thermal extremes encountered in the flying or survival environments, while others may offer minimal protection. Pressure suits do not protect against decompression sickness or the effects of trapped gases in the body. Current pressure suit technology does not provide absolute or total protection without compromising the important design criteria of mobility and comfort.

The aircrew member whose mission demands sustained flight above FL500 is relatively secure in the aircraft pressurized cabin and receives breathing oxygen at a very slight positive pressure within a specially constructed helmet. The pressure suit is basically inactive, or depressurized, and the crewmember can move the body, arms, and legs with comparative ease. If the cabin decompresses, the flyer is immediately subjected to all of the environmental stresses of the actual pressure altitude. However, when exposed to pressures at altitudes greater than FL350, the pressure suit assembly pressurizes almost instantaneously using the principles of Boyle's Law, and the crewmember is again safe.

Freedom of movement is moderately or severely impaired by the pressurized suit assembly. The degree of mobility the flyer has depends upon the type of pressure suit assembly in use and the pressure altitude to which it is exposed. Proper suit size, adequate sizing adjustments, and equipment familiarity through training are important factors that contribute to optimum mobility required to perform flight duties. Finite movements of the arms and gloved hands are difficult, even for the experienced flyer. This is due to the rigidity or constraining force of the protection it must provide.

Comfort of the flyer is of primary importance when considering the design and use of any item of protective equipment. Pressure suit assemblies pose some special problems concerning thermal stress, body water balance, impaired circulation, fatigue, cramps, and general discomfort.

The earlier designs of pressure suit assemblies that applied mechanical counterpressure directly to the surface of the body were subjectively less restricting to movement but caused superficial skin discomfort due to the pressure or pinching exerted by seams and adjustment lacings. When pressurized for long periods of time, these assemblies also reduced peripheral circulation of blood, caused tingling sensations on the body, and contributed to muscle cramps. Modifications have partially corrected these problems.

Pressure suits that cover the entire body in a virtually airtight enclosure cause an accumulation of body heat and profuse sweating unless some method of cooling is provided. Heat removal is generally accomplished by convection. Cooling air or oxygen is introduced into the suit assembly and then exhausted to the outside of the suit. Fluids for drinking are obtained by inserting tubes through a specially designed orifice in the helmet visor or shell, thereby maintaining body hydration.

8.3.5. Types of Pressure Suits

The two basic types of pressure suits are the partial-pressure suit and full-pressure suit. The former applies counterpressure directly to the body surface by means of mechanical squeeze and the latter by surrounding the body with an envelope of air or oxygen.

8.3.5.1 Partial-Pressure Suits. The development of this series of suits began in 1947, and they are called partial-pressure suits because counterpressure is applied only to the legs, torso, arms, and hands. The helmet, which seals around the neck of the user, provides breathing oxygen and pneumatic counterpressure surrounding the entire head.

The partial-pressure suit is virtually form-fitting and applies direct counterpressure when the aircraft cabin altitude exceeds FL400. The variable squeeze effect is produced by means of inflatable capstans, which extend down the back and

along the arms and legs. These tubes are attached to the suit by means of crossing tapes. The diameter of the capstan is approximately one-fifth the diameter of the area it protects. Therefore, the pressure introduced into the capstan must be five times the desired resultant pressure on the body. The objective is to supply the amount of counterpressure that will just balance the breathing pressure necessary to prevent hypoxia at a given altitude.

For example, breathing pressure of 100 mmHg, or approximately 2 psi, requires balanced counterpressure of 2 psi, obtained by applying a pressure of 10 psi to the capstan. Capstan pressures and breathing oxygen are delivered to the suit by means of a dual function oxygen regulator located in the seat kit of the aircraft. Partial-pressure suits are in limited use.

8.3.5.2 Full-Pressure Suits. The first operational full-pressure suit was produced for the U.S. Navy during the 1950s and has been succeeded by a number of other specially designed models. The full-pressure suit, helmet, and gloves surround the body with a pressurized gas envelope to provide counterpressure usually when the aircraft cabin altitude exceeds FL350 (Fig. 8.3.5-1).

Since the flyer is completely within the suit assembly, counterpressure and oxygen breathing pressure are metered at a ratio of approximately 1:1. Most full-pressure suits are unpressurized until the cabin altitude exceeds FL350. When the cabin altitude exceeds FL350, a suit-mounted controller senses the decreasing pressure and automatically causes the suit to inflate to a given pressure which, when added to the ambient pressure at that altitude, equals about 3.4 psi (FL350 equivalent). Therefore, a flyer wearing a full-pressure suit is never exposed to a pressure altitude greater than FL350, regardless of aircraft altitude.

Figure 8.3.5-1. Full Pressure Suit

Special Modified Underwear. Each U-2 aircrew member is supplied modified long cotton underwear, modified jockey briefs, thin nylon or cotton gloves, and wool socks. The underwear modification consists of a hole cut out in the front of the bottoms to accompany a urine collection device (UCD). The hole is surrounded by the soft part of Velcro. This holds the UCD in place. If a UCD is not worn, then a patch is placed on the hole.

UCD and Urine Collection System (UCS). The duration of U-2 missions requires the flyer to be able to void urine while in the FPS assembly. The UCD is effectively an external catheter while the UCS has the form of a maxi-pad with a drainage tube that connects to the external valve assembly on the FPS leg. The UCD has a cone-shaped portion that is trimmed for size by the aircrew member to fit comfortably on the penis. It is then held in place by the modified underwear. There is a hole positioned on the top of the UCD to allow air from a slightly pressurized pressure suit to enter and then pass out the front of the UCD through a tube. It then passes through the pressure suit at the UCD valve and into a tube, which leads to a urine collection tank or a urine collection sponge device. This piece of personal equipment is washed and maintained by the aircrew member.

Full-Pressure Suit Assembly. The full-pressure assembly comes in 12 sizes and can be fine tuned in size through lace adjustments on the legs, arms, and torso. Each aircrew member is issued two pressure suit assemblies, called an S1030 or S1031, but only one helmet. This assembly has a comfort layer that is held in place by Velcro and is periodically removed and washed. The fire retardant outer cover is a treated material called fypro. This cover is removed occasionally and washed. The aircrew's primary suit undergoes a 25-min preflight check, and the back-up suit is given a cursory inspection prior to each high flight. A periodic inspection is conducted every 120 days, 125 flight hours, or 20 donnings.

The inspection is extensive and takes about 4 hr to complete. Each suit is overhauled annually. This entails an extensive breakdown of the suit, an 8-psi stress test, replacement of worn parts, and replacement of diaphragms. Recalibrations of various functions of the dual oxygen regulator and suit pressure controller are also necessary. The overhaul of these two pieces of hardware is very delicate work and requires a highly trained and skilled PSD technician. Maintaining the neck ring can be quite time consuming due to the approximately 122 ball bearings and nylon spacers that have to be removed, cleaned, and reinserted one at a time. The 36-mo overhaul requires about 8 man-hr to complete.

Pressure Suit Helmet. Each crew member is issued one helmet. Several additional helmets are maintained and periodically inspected to serve as back-ups in case the aircrew's helmet has a mechanical problem during the suit up. All the helmets are the same size. Sizing is accomplished by different thickness helmet liners. The helmet is a fairly complex portion of the pressure suit system that requires considerable maintenance. Individual items that require a fair amount of maintenance and care include the exhalation valve; the anti-suffocation valve; and the dual oxygen regulator, which is located in the back of the helmet. Maintaining the correct adjustment of the bailor bar (visor lock down lever) is also critical. The visor must be kept scrupulously clean. The microphone and ear phones in the helmet liner are notorious sources of problems and must be carefully maintained and inspected.

Gloves. Each crew member is issued three pairs of gloves. Gloves used to be constructed by PSD personnel and took about 30 min to make each glove. Now the gloves come almost preconstructed. Each glove takes an average of 10 min to make when several are built at one time.

Torso Harness. Each aircrew member is issued two of these harnesses. This harness contains the support webbing and parachute koch fittings to attach the crew member to his/her 35-ft canopy parachute. It also contains the automatic personal flotation device. This harness also undergoes certain periodic inspections.

Boots and Spurs. Each crew member is issued a pair of insulated boots two sizes larger than normal. This enables the pressure suit bootie to inflate in the boot. A set of spurs is attached to the heel of the boot during the dressing process and secured by nylon straps and Velcro. This spur is then attached to a ball and cable device attached to the ejection seat to prevent leg flailing during bailout. These items take very little maintenance and are replaced when worn out.

Tube Food and Drinking Bottles. In cooperation with the Army Natick food laboratory, pilots are provided over 2 dz choices of foods to consume during flight. The caloric intake is made through a feeding port in the helmet to prevent breaking the seal on the visor. This feeding port is automatically closed when not in use. When food or drink is required, the “tube food” with a feeding “pon tube” attached or a water bottle filled with various beverages is inserted into the feeding port. The specific manufacture

date must be monitored to ensure freshness. The aircrew's food and drink requirements have to be coordinated prior to every flight. After flight the water bottles have to be washed and sterilized to be used again.

Survival Kit. The survival kit used in the U-2 is unique. Besides the standard components of a life raft and survival items, the kit houses two 2,200-psi, 45-cu in. oxygen cylinders. These provide oxygen during bailout or when required to supplement a malfunctioning aircraft oxygen system. The cylinders provide about 30 min of oxygen if there is no significant leak in the suit.

Parachute. The parachute used in the U-2 has a 35-ft canopy to accommodate the extra weight of the FPS and survival kit. The parachute pack and harness are inspected daily by PSPTS personnel prior to being used on a flight. This inspection takes about 10 min. The parachute is installed and removed from the cockpit daily by PSPTS personnel. Parachute repack and repairs are accomplished by the local parachute shop.

LOX Cooler. The LOX cooler is used as a portable source of 100% breathing oxygen and a source of ventilation air. It weighs 35 lbs when full of the 2.5 L of LOX.

8.3.6. Training for the Dragon Lady (U-2) Pilot

The 9th PSPTS conducts physiological training for U-2 pilots in parallel with standard AFI 11-403 requirements. Due to the unique nature of the mission and hostile nature of the high-altitude environment, the curriculum is adapted to the needs of the pilot. From acceptance to the U-2 program, the pilot enters a series of specialized training programs. All SERE training (water and land survival) is reaccomplished locally and tailored to the wear of the full-pressure suit.

The altitude chamber training is outlined in ACCI-11-459 and includes a chamber flight to FL750 and rapid decompression from FL295 to FL630. The profile includes a hypoxia experience, fit and function checks of the FPS, and emergency procedures (BOLDFACE) check while in the chamber. The training is conducted one-on-one with the pilot integrated to an ejection seat mock-up and realistic oxygen and survival kit configuration.

Technicians assigned to the 9th PSPTS also undergo FPS training. If qualified, the technician will complete the same phase of FPS orientation that the pilot does in an effort to provide the qualified technician a solid foundation of the physiological stresses of being inside a FPS.

8.3.7. Radiation

Galactic cosmic radiation from outside the solar system can have a negative impact on human physiology. An occasional disturbance in the sun’s atmosphere may also lead to a surge in radiation particles. Protection from both sources is provided by the magnetic fields of the sun and the earth and the Earth’s atmosphere. Dose rates are dependent on the altitude, the geomagnetic latitude, and the solar cycle. There are conflicting reports about the relationship between some forms of cancer and high altitude (>30,000 ft) flight (Ballard et al., 2000; Diffey & Roscoe, 1990). Concern about exposure of U-2 pilots while flying in the stratosphere is similar to the concern expressed about exposure of Concorde pilots on long-duration flights. Twenty years of radiation monitoring in the British Airways Concorde established that flight crew exposure levels were well under the occupational dose limit of 20 mSv/y recommended

by the International Commission on Radiological Protection (Bagshaw et al., 1996). Further, epidemiological studies of flight crew have not shown conclusive evidence for any increase in cancer mortality or cancer incidence directly attributable to ionizing radiation exposure (Bagshaw, 2008).

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Recommended Reading

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Concepts

- 9th Physiological Support Squadron (PSPTS)
- High-altitude reconnaissance mission support (HARMS)
- Radiation

Vocabulary

- Dragon Lady (U-2)
- Full-pressure suits
- Partial-pressure suits
- Urine collection device (UCD)

8.4. Safety and Accident Investigation

Col Donald J. White, USAF, BSC

8.4.1. DoD Human Factors Analysis and Classification System (HFACS)

8.4.1.1 Executive Summary of a Mishap Investigation and Data Analysis Tool. This Department of Defense Human Factors (DoD HF) guide explains procedures for investigating and reporting all DoD mishaps. It supports DoDI 6055.7, Accident Investigation, Reporting, and Record Keeping. The DoDI directs DoD components to "Establish procedures to provide for the cross-feed of human error data using a common human error categorization system that involves human factors taxonomy accepted among the DoD Components and U.S. Coast Guard." It is intended for use by all persons who investigate, report, and analyze DoD mishaps and is particularly tailored to the needs of persons assigned to Interim Safety Boards and formal Safety Investigation Boards following all classes of mishaps. There are myriad potential human factors, all of which need to be assessed for relevancy during a mishap investigation. No investigator, flight surgeon, physiologist, human factors consultant, or aviation psychologist can be expected to be fully familiar with all potential human factors.

When using this human factors model, the investigator should consider applying the model to three distinct areas of consideration: environmental, individual, and the event or mishap. The mishap crew, operator, or team reacts to the environment to which they are exposed. The environmental factors cover not only the physical environment to which the individual members are exposed but also the organizational and supervisory environments and specific physical and technological preconditions. The individual factors cover acts, precondition, and supervision factors. The mishap factors can cross all four tiers of the model. The investigator can apply this model by entering at any tier that is specifically related to environmental, individual, or mishap factors discovered during the analysis. This model can be used as either a primary or secondary tool to investigate both active and latent failures. Our model is designed to present a systematic, multidimensional approach to error analysis. This human factors model covers human error from three perspectives:

- Cognitive Viewpoint and Human System Interaction and Integration
- Human-to-Human Interaction
- Sociocultural and Organization

When using our DoD HF taxonomy for either primary investigation or secondary analysis, we must assume error can mean several things:

- Error as the failure itself. For example: The operator's decision was an error (decision, perceptual, or skill-based errors).
- Error as the cause of failure. For example: This event was due to human error (failure to provide guidance).
- Error as a process or, more specifically, as a departure from some kind of standard (exceptional, routine, intentional, or unintentional).

A reasonable synthesis of these assumptions, as suggested by Senders and Moray (1991), is the following: Human error occurs when human action is performed that was either (1) not intended by the actor, (2) not desired according to some specified set of rules or by some external observer, or (3) contributed to the task or system "going outside its acceptable limits."

This DoD guide starts with a brief history of the development of the DoD HFACS, followed by an introduction and description of the human factors and human performance application of this model. The guide concludes with a high-level structural overview of the taxonomy and definitions.

8.4.1.2 Introduction. Mishap or event investigation can be extremely difficult, time-consuming, and stressful, but it can also be rewarding when we recognize that the contributions we make will improve safety. A thorough mishap investigation is absolutely necessary to determine the cascading events causal to a mishap and to recommend corrective actions to prevent recurrence. This guide provides the accident investigator with a proven template that aids in organizing the investigation while providing a detailed analysis of human error for on-scene investigation and post-hoc mishap data analysis, revealing previously unidentified human error trends and hazards.

Human error continues to plague both military and civilian mishaps. Analysis indicates that human error is identified as a causal factor in 80% to 90% of mishaps and is present but not causal in another 50% to 60% of all mishaps and is, therefore, the single greatest mishap hazard. Yet, simply writing off mishaps to "operator error" is a simplistic, if not naïve, approach to mishap causation and hazard identification. Further, it is well established that mishaps are rarely attributed to a single cause or, in most instances, even a single individual. Rather, mishaps are the end result of myriad latent failures or conditions that precede active failures (Naval Flight Surgeon's Pocket Reference to Aircraft Mishap Investigation). The goal of a mishap or event investigation is to identify these failures and conditions to understand why the mishap occurred and how it might be prevented from happening again.

8.4.1.3 Description. This guide is designed for use as a comprehensive event/mishap, human error investigation, data identification, analysis, and classification tool. It is designed for use by all members of an investigation board to accurately capture and recreate the complex layers of human error in context with the individual, environment, team, and mishap or event.

In the past, investigators have thrown human factors analysis to the medical investigators and have asked them to do this work on their own. This practice has sometimes produced human error analyses that differed considerably from the board's investigation and findings of fact. Integrating human factors analysis into all aspects of the investigation will result in a much more coherent final product.

As described by Reason (1990), active failures are the actions or inactions of operators that are believed to cause the mishap. Traditionally referred to as "error," they are the last "acts" committed by individuals, often with immediate and tragic consequences. For example, an aviator forgetting to lower the landing gear before touchdown or showing off through a box canyon will yield relatively immediate, and potentially grave, consequences. In contrast, latent failures or conditions are errors that exist within the organization or elsewhere in the supervisory chain of command that affect the tragic sequence of events characteristic of a mishap. For example, it is not difficult to understand how tasking crews or teams at the expense of quality crew rest

can lead to fatigue and ultimately errors (active failures) in the cockpit. Viewed from this perspective then, the actions of individuals are the end result of a chain of factors originating in other parts (often the upper echelons) of the organization. The problem is that these latent failures or conditions may lie dormant or undetected for some period of time prior to their manifestation as a mishap.

The question for mishap investigators and analysts alike is how to identify and mitigate these active and latent failures or conditions. One approach is the "Domino Theory," which promotes the idea that, like dominoes stacked in sequence, mishaps are the end result of a series of errors made throughout the chain of command.

A "modernized" version of the domino theory is Reason's "Swiss Cheese" model, which describes the levels at which active failures and latent failures/conditions may occur within complex flight operations (see Figure 8.4.1-1). Working backwards from the mishap, the first level of Reason's model depicts those Unsafe Acts of Operators (operators, maintainers, facility personnel, etc.) that ultimately lead to a mishap. Traditionally, this is where most mishap investigations have focused their examination of human error and, consequently, where most causal factors are uncovered. After all, it is typically the actions or inactions of individuals that can be directly linked to the mishap. Still, to stop the investigation here only uncovers part of the story.

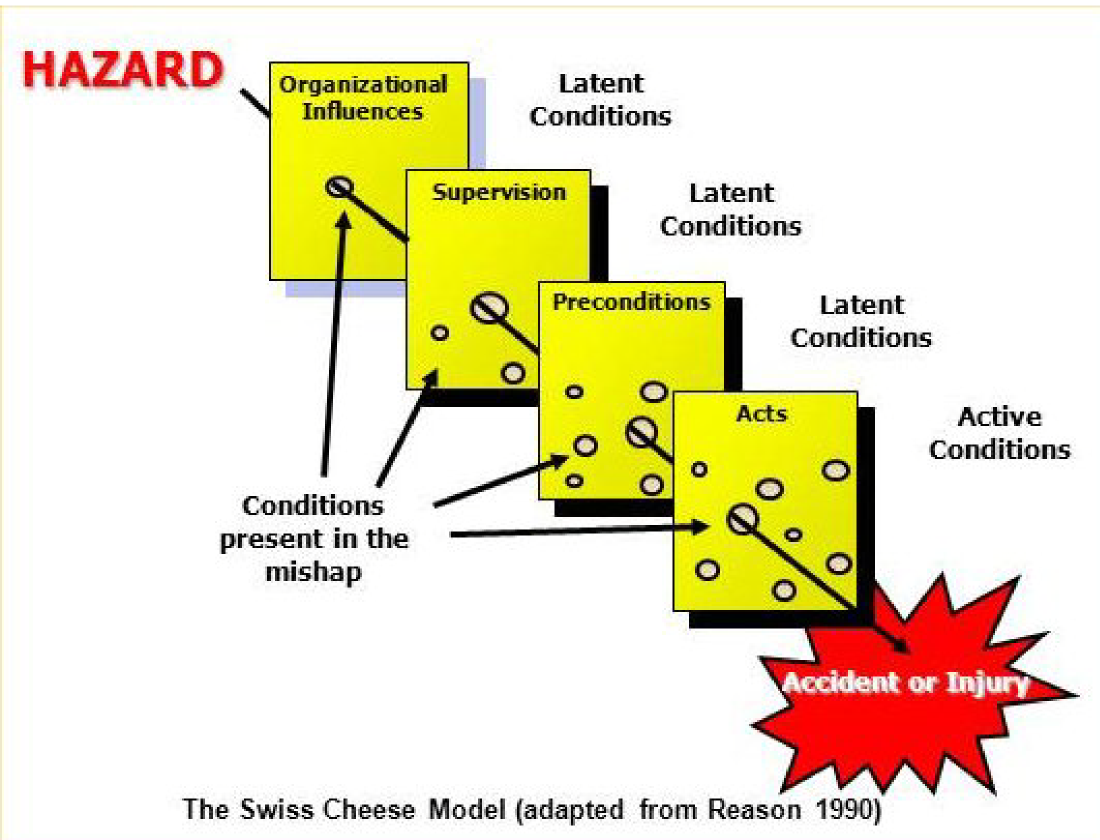

Figure 8.4.1-1. The "Swiss Cheese" Model (adapted from Reason, 1990)

What makes Reason's model particularly useful in mishap investigation is that it forces investigators to address latent failures and conditions within the causal sequence of events. For instance, latent failures or conditions such as fatigue, complacency, illness, and the physical/technological environment all affect performance but can be

overlooked by investigators with even the best of intentions. These particular latent failures and conditions are described within the context of Reason's model as Preconditions for Unsafe Acts. Likewise, Supervision can promote unsafe conditions of operators and ultimately unsafe acts will occur. For example, if an operations officer were to pair a below average team leader with a very junior/inexperienced crew, the result is increased risk of mission failure. Regardless, whenever a mishap does occur, the crew naturally bears a part of the responsibility and accountability. However, latent failures or conditions at the supervisory level are often equally responsible for poor hazard analysis and subsequent increased mission risk and may ultimately cause the mishap. In this particular example, the crew was set up for the opportunity for failure.

Reason's model does not stop at supervision; it also considers Organizational Influences that can impact performance at all levels. For instance, in times of fiscal constraints, funding may be short and may lead to limited training opportunities. Supervisors are sometimes pressed to task "nonproficient" crews with complex missions. Not surprisingly, unintended and unrecognized errors may appear, and mission performance will consequently suffer. As such, hazards and risks at all levels must be addressed if any mishap investigation process is going to be effective.

The investigation process then endeavors to detect and identify the "holes (hazards) in the cheese" (see Figure 8.4.1-1). So how do we identify these hazards? Aren't they really too numerous to define? After all, every mishap is unique, so the hazards will always be different for each mishap ... right? Well, it turns out that each mishap is not unique from its predecessors. In fact, most mishaps have very similar causes. They are due to the same holes in the cheese, so to speak. The hazards identified in each new mishap are not unique to that mishap. Therefore, if you know what these system failures/hazards or "holes" are, you can better identify their roles in mishaps -- or better yet, detect their presence and develop a risk mitigation strategy correcting them before a mishap occurs.

8.4.1.4 Department of Defense (DoD) Human Factors Analysis and Classification System. Drawing upon Reason's (1990) and Wiegmann and Shappell's (2003) concept of active failures and latent failures/conditions, a new DoD taxonomy was developed to identify hazards and risks. It is called the DoD Human Factors Analysis and Classification System (DOD-HFACS) and describes four main tiers of failures/conditions: (1) Acts, (2) Preconditions, (3) Supervision, and (4) Organizational Influences (Figure 8.4.1-1). A brief description of the major tiers with associated categories and sub-categories follows, beginning with the tier most closely tied to the mishap.

References

Naval Flight Surgeon's Pocket Reference to Aircraft Mishap Investigation. The Naval Safety Center, Aeromedical Division. Fifth edition, 2001.

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Wiegmann DA, Shappell SA. A human error approach to aviation accident analysis: The human factors analysis and classification system. Burlington, VT: Ashgate. 2003.

Concepts

DoD Human Factors Analysis and Classification System (HFACS)

8.5. Chamber Training

8.5.1. Hypoxia Experience

8.5.1.1 Philosophy of Hypoxia Training and the Reduced Oxygen Breathing Device. Since the earliest balloonists raised their gondolas to lofty heights above the Earth, the awareness of the effects of rarified air on human physiology has been documented. As aviators pointed the nose of their aircraft skyward and ascended to altitudes above 10,000 ft, then 18,000 ft, and again to a range above 20,000 ft without pressurization systems, oxygen systems and personal attention to the conditions linked to hypoxia have captured the attention of scientists and accident investigators alike. The environment universally accepted for hypoxia "training" is the hypobaric chamber. As an extension of the classroom, the altitude chamber is a training device that places the student at a designated altitude above field elevation. As the altitude climbs, the student completes a series of prescribed tasks including an hypoxic experience at 25,000 ft. The altitude chamber flight affords the student the opportunity to experience mild hypoxia, gas expansion, environmental temperature changes, practice with oxygen equipment, and demonstration of night vision.

The advent of the reduced oxygen breathing device (ROBD) has provided a new platform for hypoxia training into the 21st century. The introduction of a mixed gas during flight simulation places the crew member in a part-task training environment with the backdrop of a realistic flight scenario. The ROBD will be used only as a means of refresher physiological training where available and appropriate for the aircraft type (e.g., single and dual seat). While guiding a scripted profile on a flight simulator program, the ROBD operator will introduce a gas mixture representative of the ambient air conditions at the altitude of the simulation. The specific details of operation are part of a formal training program for aerospace and operational physiology staff. Once the crew member notices any change in performance or physiological conditions related to hypoxia, corrective actions are begun ("pilot demonstrates Emergency Procedures"), and the ROBD operator selects "100% Oxygen" on the device and monitors the student through recovery. The portable system does not replace the altitude chamber for the initial hypoxia experience but provides a flexible platform that can be co-located with squadrons without regard to chamber facilities.

Specific chamber flight profiles are described in AFI 11-403 (Aerospace and Operational Physiology Program), and objectives will be briefed in the classroom prior to each flight.

8.5.1.2 Sample Chamber Flight Lesson.

BEGIN DENITROGENATION TIME (with concurrence from inside observers):

- Ensure all regulators are set to ON and 100% position. Caution students NOT TO DROP their masks or move the switches on the regulator.

INTERCOM CHECK:

- Perform intercom check with students/crew
    - Explain intercom system. There are two ways to communicate. One button is below the three switches on the regulator and the other button is located by the CRU 60P.
    - Have students give their NAME and SEAT POSITION (COMM).
    - Next have the IO's and outside crew do a COMM check on the COMM channel.
    - In case of intercom failure, you will need to use hand signals to the inside observers.

BEFORE THE FLIGHT BEGINS:

- Have everyone practice doing a Valsalva.

DENITROGENATION:

- Conduct ear and sinus check.
    - Explain the reason why we conduct an E&S check from GL to 5,000 ft. GL to 5,000 is the area of the greatest pressure change in the Earth's atmosphere. If everyone is able to make it through the ear and sinus check without any problems, then they should be able to complete the entire chamber flight profile without any problems.
    - Have inside observers demonstrate "level-off" signal.
    - Remind students that they shouldn't need to accomplish the Valsalva maneuver on ascent. Middle ears normally clear automatically. To help assist with pressure equalization, you could yawn, swallow, or move your jaw from side to side.
    - Point out training aids.
        - Explain the Flask/Beaker arrangement if applicable or use a different training aid to show problems with trapped gases in the middle ears and sinuses. Tell students that they should not fly with a cold.
        - Gloves hanging in the chamber will increase in size as we go up in altitude in accordance with Boyle's Law.
        - If there is an altimeter inside the chamber, describe how students can reference it to have a general idea of the altitude that they are passing through. Don't forget to remind the students that the altimeter inside the chamber has been through a few rapid decompression profiles and it is not as accurate as the equipment that we have on the outside of the chamber.

- At 5,000 ft ask students if they have any problems with the ascent portion of the flight. Ask for a “thumbs up” from the students and observers before beginning descent.
- On descent remind the students that they need to do something to clear their ears because their ears will not clear automatically while the pressure is increasing.
  - To do an effective Valsalva, keep your head straight or tilted back slightly, with your two forefingers or thumb and forefinger, pinch off the Valsalva ports on the mask and blow. The maneuver should be short and forceful. If you have a slow ear, put the slow ear up towards the ceiling and do a short and sharp Valsalva.
  - The other ways to clear your ears include yawning, swallowing, wiggling your jaw back and forth, or delivering pressure from the regulator.
  - Remember the level off sign, if you have a problem.

PRICE CHECK (relate to specific aircraft):

DO a PRICE CHECK (1) before the aircraft leaves the ground, (2) during flight, and (3) whenever hypoxia occurs or after a decompression occurs.

- P - Pressure
  - Low-Pressure Gaseous - Yellow
    - Full pressure: 425 $\underline{+}$ 25 psi
    - Operationally empty: 100 psi; Maintenance empty: 50 psi
  - High-Pressure Gaseous - Green
    - Full pressure:
      - ◊ 1800 – 2,000 psi (A/C)
      - ◊ 1,800 – 2,200 psi (Emergency)
  - Liquid Oxygen - No Color Code
    - Low pressure: 50 - 120 psi (Fighter)
    - High pressure: 300 psi (Multiplace A/C)
    - Quantity gauge:
      - ◊ Full: 95% of converter capacity
      - ◊ Empty: 10% of converter capacity
    - Expansion ratio: 860:1/gas:liquid
- R - Regulator
  - Fly to fail equipment - Do thorough inspection
  - Visual inspection:
    - Cracks in face/cover
    - Oil or grease (petroleum products)
    - Broken switches.
  - Functional inspection:
    - Switches move easily and stay in desired settings
    - Integrity check:
      - ◊ All 3 switches up - On - 100% Oxygen - Emergency
      - ◊ Three breaths - Hold - Monitor indicator
      - ◊ Follow same procedures with automix lever in “normal" setting - Monitor indicator

- I - Indicator
    - Automix lever at 100% setting
    - Monitor for smooth operation
    - Uses:
        - Gas flow through system
        - Leak check on system
        - Monitor breathing rate
- C - Connections: Start as far back as possible and work toward the helmet (habit forming). Remind students to use positive checks.

NOTE: DO NOT ALLOW THE STUDENTS TO DISCONNECT DURING DENITROGENATION

- Check CRU-60/P for:
    - 12 - 20 lb disconnect tension - first connect the CRU 60/P with ship supply and then disconnect; from that point on all checks will be positive checks
    - Silver "C" ring
    - Neoprene washer: Color is green, rust (orange), or white
    - O-ring
    - Emergency oxygen hose connector
- Oxygen Equipment/Intercom System:
    - Inspect mask hose for holes, kinks, and cuts (wear and tear).
    - Inspect intercom cord that is wrapped around mask hose.
        - Check Intercom cord for cuts, kinks, and frays.
        - Check all intercom connections (positive).
    - Bayonets set in receivers with two clicks - If you get your own oxygen rquipment the oxygen mask straps will be tacked down by Life Support (your equipment).
    - Chin strap
- E - Emergency- Do a PRICE CHECK on ALL emergency equipment.
    - Low-pressure systems: MA-1 portable oxygen assemblies (what is commonly called the Walk a Round Bottle)
        - Color code - Yellow, check the condition of the bottle.
        - Check the pressure: The pressure will be whatever the line pressure of the aircraft.
        - If the pressure is 50 psi or lower, for longer than 2 hr, then you must purge the system. Fill and empty the bottle 3 times.
        - Lift the dust cover up and look inside. Things could be in it.
        - Provides a certain amount of oxygen to the user.
        - Refiller ports on aircraft: Know where they are and how to use them.
        - Refill whenever the walk around bottle is at 100 psi or lower.
    - High-pressure systems: High-pressure emergency cylinder
        - Color Code - Green, check the condition of the bottle.
        - Check the pressure: The pressure will be 1,800-2,200 psi.
        - Also check the nozzle, hose, green apple, and red tag.
        - Once activated, it gives a 10-min continuous flow of oxygen.
        - The pressure you fill in the chamber may not be the actual pressure you will fill when activating a real bottle.

- Check ALL emergency oxygen sources: Could be an extra regulator, passenger oxygen kit (POK), personal breathing device (PBD), sodium chlorate candle.
- Extra regulator - do a PRICE CHECK.
- Passenger Oxygen Kit (POK): A green bag with a high-pressure emergency cylinder and oxygen mask. You would check everything that you normally check with the high-pressure emergency cylinder and also do an inspection of the mask.
- Personal Breathing Device (PBD) - Four major components:
  - Solid state oxygen supply source
  - Chemical scrubber for carbon dioxide and vapor
  - Loose-fitting hood with head harness and neck seal to provide the breathable environment
  - Pumping arrangement powered by the chemical oxygen, which recirculates the breathing gas within the scrubber and hood
  - One time use, totally self-contained. Duration is approximately 15 min.
  - To use: Remove unit from container, tear off pull strip, and remove from plastic wrapper. Pull actuation ring. Hold device by open end, with supply pack away from you. Bend over and grasp hood opening with thumbs; pull overhead. Rise to standing position and adjust hood and pack for comfort. Check neck seal for secure fit. Remove and stow on aircraft after use.
- Sodium Chlorate Candle: Chemical Generated Oxygen
  - Mainly a passenger source, stowed under seat on cargo compartment pallets.
  - System contains pull out passenger mask with polyvinyl bag. Duration is 30 min. This system consists of canister containing a fuel-enriched cone and a sodium chlorate candle and a mask with bag.
  - To use: Activate by pulling mask from canister, thereby breaking lanyards that trigger striking pins, which activate chemical generation.
- Any personal gear available

NOTE: Ensure that a full 30 min of denitrogenation has been completed and perform student and crew intercom check prior to ascent to FL250 (Table 8.5.1-1).

ASCENT TO FL250:

- Have students stretch out prior ascent.
- Discuss the value of frequent intercommunication checks in chamber and aboard military aircraft.
- Remember no Valsalvas on ascent. Ears will pop and click (clear) automatically.
- If there are any problems remember the level off signal.
- AFI 11-202v3, General Flight Rules, Chapter 6, Life Support Systems, Paragraph 6.4.1 states that “each crewmember SHALL use supplemental oxygen anytime the cabin altitude exceeds 10,000 feet.” Chapter 6 also discusses oxygen requirements when you are flying in helicopters, unpressurized aircraft, and pressurized aircraft.

INFORMATION FOR AEROMEDICAL EVACUATION CREWMEMBERS:

Message also came out that states all primary aeromedical evacuation crewmembers will have a portable walk around bottle at their flight position for preplanned flights above FL350.

Table 8.5.1-1. Oxygen Requirements[a] for Pressurized Aircraft (AFI 11-202v3)

Altitude	Pilot	Flight Engineer	Other Flight Deck Crew	Cabin/Cargo AreaCrew	Pax
10,000 ft through FL250	R	R	R	A	N/A
Above FL250 through FL350	One I One R	I	R	A	A
Above FL350 through FL410 (both pilots in seat)	I	I	R	A	A
Above FL350 through FL410 (only one pilot in seat)	One O One A	I	R	A	A
Above FL410 through FL450	One O One I	I	R	A	A
Above FL450 through FL500	One O One I	I	I	A	A
Above FL500 through FL600 (pressure breathing for altitude system/get me down scenario)	G	G	G	G	G
Above FL500 (sustained)	S	S	S	S	S

[a]**A – Have Oxygen Available**: Individuals required to have oxygen available must carry portable oxygen (such as walk around bottles) on their person any time they are moving about the cabin/cargo area. The requirement to have oxygen available can also be satisfied by placing sufficient portable oxygen units or extra oxygen outlets with masks throughout the cabin/cargo area so that any crew member or passenger has quick access to oxygen regardless of where he/she is in the cabin/cargo area should a loss of pressurization occur.

R – Have Oxygen Readily Available: Individuals required to have oxygen readily available must have a functioning system and mask located within arms reach, and the regulator must be set to 100% and ON.

I – Have Oxygen Immediately Available: Crew members who are required to have oxygen immediately available must wear helmets with an oxygen mask attached to one side or have available an approved quick-donning/sweep-on mask properly adjusted and positioned. Regulator shall be set to 100% and ON.

O – Oxygen Mask ON: Regulator ON and Normal.

G – Wear a Partial Pressure Suit: Suit must provide 70 mmHg of assisted positive pressure breathing for altitude.

S – Wear a Pressure Suit: Suit must provide a total pressure (atmospheric plus suit differential) of at least 141 mmHg to the head and neck with adequate body coverage and pressurization to prevent edema and embolism.

Given the shortage of the MA-1 portable oxygen bottles, the emergency passenger oxygen system, protective breathing equipment, or emergency escape breathing device can be used for preplanned flights below FL350 as a primary oxygen source.

- At 16,500 ft, explain that wet gas expansion is double – pass the gas.
- At 18,000 ft, explain that dry gas expansion is double, also half the Earth's atmosphere, and refer to altitudes by flight levels (i.e., FL180).
- Trapped gases that you have are middle ear, sinuses, teeth, and gastrointestinal tract.
- Approaching FL250
  - o Highest altitude that an unpressurized aircraft can go (T-37).
  - o Hypoxia becomes critical factor, FL180 effective performance time (EPT) 20-30 min, EPT or time of useful consciousness (TUC) at FL250 is 3 to 5 min.
  - o Evolved gas decompression sickness is more likely to occur above FL200.
    - ◊ Limb pain symptoms
    - ◊ Skin symptoms
    - ◊ Respiratory symptoms
    - ◊ Neurologic symptoms

NOTE: IAW AFI 11-202v3, General Flight Rules (5 Apr 06), Chapter 6, paragraph:

6.4.5.4. If an individual appears to be suffering decompression sickness, a crew member should administer 100 percent oxygen to that individual using a tight fitting aviator's oxygen mask.

6.4.5.4.1. If an aviator's mask is not available, an alternate source that can provide the greatest percentage of oxygen delivery should be used.

6.4.5.4.1.1. Individuals suspected of decompression sickness should remain on 100 percent oxygen until evaluated by a flight surgeon or competent medical authority.

6.4.5.4.2. The pilot must descend as soon as practical and land at the nearest suitable installation where medical assistance can be obtained. Decompression sickness may occur up to 12 hours after mission completion. The affected person shall not continue the flight unless authorized by a flight surgeon or civilian designated aviation medical examiner.

6.4.5.5. After a cabin decompression, the risk of decompression sickness increases with prolonged exposure to altitudes at or above FL 210 (unpressurized).

LEVEL AT FL250:

NOTE: Minimize lecture during demonstration to allow students to focus on symptoms. Do not give any time hacks as this may affect a student's decision to recover instead of keeping track of hypoxia symptoms he/she may be experiencing.

- Explain how the hypoxia demonstration will work. Everyone will go off oxygen. Drop mask from right side and turn regulator off.
- To correct for hypoxia, put all three switches on regulator up. Remember to slow your breathing down. Put the red level in normal position once all symptoms are gone.

START CLOCK FOR TIME (Maximum Time OFF – 10 min)**:**

- Remind students that there is no prize for who can remain off of oxygen for the longest amount of time. Tell them that the goal is to recognize hypoxia and correct for themselves.
  - o EPT at FL250 is 3 to 5 min.
  - o To remain off oxygen too long could result in their forgetting the symptoms just received or result in a moderate to severe headache.
  - o Students monitor and help one another while observing "outward" symptoms of hypoxia.
- Discuss common recognition symptoms of hypoxia.
  - o Objective symptoms (OUTWARD SIGNS, what others can observe)
    - ◊ Increased rate and depth of breathing
    - ◊ Cyanosis (bluing) of lips and fingernail beds
    - ◊ Unconsciousness
  - o Subjective symptoms (WHAT ONLY YOU FEEL)
    - ◊ Apprehensive feeling
    - ◊ Dizziness
    - ◊ Fatigue
    - ◊ Nausea – correct immediately if you feel this
    - ◊ Hot & cold flashes
    - ◊ Blurred vision
    - ◊ Tingling and/or numbness
    - ◊ Euphoria or belligerence

DESCENT FROM FL250 TO FL180:

- Ensure a normal descent rate Explain that they will be doing the visual acuity demonstration.

PASSING THROUGH FL220:

- All students remove oxygen mask from right hand side of face.
- Lecturer, observer, and recorder start stopwatches.
- Have inside observers (IOs) pass out visual acuity cards.
- Students should be advised to place cards upside down on their lap (white side up).

LEVEL AT FL180 – VISUAL ACUITY DEMONSTRATION:

- Turn off main chamber lights.
- Dim emergency lights via rheostat on chamber's main console (ONLY WHEN LIGHTS ARE NOT PREADJUSTED).
- **Tell students that if they feel their hypoxia symptoms with the same intensity that they felt at FL250 to abort the demonstration, get back on oxygen, and notify the IOs of their problem.**

- Explain that the main purpose of this demonstration is to illustrate the dramatic loss of vision, especially in a low illumination environment. Simulates flying at about 9,000 ft for 4 hr. We take you to FL180 for 5 min. EPT at FL180 is 20-30 min.
- The students may feel that their vision is improving after a minute or two, but you as the lecturer must remind them that they are becoming slightly hypoxic (double edge sword effect).
- Explain that as light intensity decreases, colors gradually begin to disappear. Vision usually is affected by the lack of oxygen, and this demonstration will show this to you. Visual acuity decreases by 25% at 10,000 ft.
- Explain that peripheral vision and loss of color vision deteriorate in a darkened environment.
- Have students look around the chamber. Look at the number across from you on the wall.
  - Have students turn cards over and fixate their vision on the mini vision chart in the center.
  - Instruct students to take note of their peripheral vision.
    - ◊ "Zs" around periphery of card begin to fade or completely disappear.
    - ◊ Turn card over and notice colors on the map (chart).
  - Instruct students to note changes or merging of colors on card.
- 5-min point:
  - Have students replace oxygen mask (with free hand) while still focusing on center of card.
  - Instruct students to note any changes in their vision.
- 20-s mark:
  - Have students place cards back in their laps and reconnect masks to helmet.
  - Gradually turn up chamber lighting; advise students to shield eyes.
  - End demonstration with questions concerning changes in vision.
- After terminating demonstration, ensure that all students have the regulator in the ON (green switch up) and NORMAL setting (white automix lever down).
- Discuss what happened during the visual acuity demo. Oxygen paradox is a phenomenon that typically occurs during the visual acuity demonstration. Explain why most of the students experienced oxygen paradox, if applicable.

AFTER THE VISUAL ACUITY DEMONSTRATION: Dial up pressure for High-Pressure Demonstration/HIGH-PRESSURE OXYGEN CYLINDER DEMONSTRATION:

Chamber will stay level until students are comfortable with demonstration.

- Have students attach emergency cylinder mockup to their CRU-60/P connector.
- Have students locate the Green apple.
- Have students PULL APPLE 1 to 2 in. – Activate the emergency oxygen system (cylinder).
  - Lean back if you're getting pressure.
  - Use your positive breathing techniques.
    - ◊ Disconnect the CRU-60/P from the ship supply hose.

BEGIN DESCENT TOWARDS GROUND LEVEL:

- Ensure a normal descent rate.
- Remind students to Valsalva.

PASSING THROUGH FL180:

- Dial pressure down.
- Explain about the system. The system lasts 10 min. It delivers 10 to 12 L of oxygen. During the first minute, after it's been activated, it will deliver 12 to 14 in. of water pressure. It will become easier to breathe after a while.
- Tell students to look at bottom of CRU-60/P.
  - o Prongs should move when they try to breathe.
  - o Plug CRU-60/P back into ship supply hose.

MA-1 PORTABLE OXYGEN ASSEMBLIES DEMONSTRATION:

- Have students practice using MA-1 portable oxygen assemblies (yellow walk around bottles).
- Direct each student to compete a mini PRICE CHECK on the assemblies.
  - o Look at bottle, check pressure, inspect CRU-60P receptacle on bottle for foreign objects before making connection.
  - o Have students dial in various pressures from bottle.
  - o Duration will vary based on altitude, your activity, pressure of bottle prior to use.
- At conclusion of demonstration, ensure that students have plugged CRU-60P connectors back into chamber oxygen supply hose and that all bottles are set to NORMAL configuration.

BELOW 10,000 FT HAVE STUDENTS DROP THEIR MASKS.

REGULATOR INTEGRITY DEMONSTRATION:

- Instruct students in the differences between the old regulator (CRU-68) and the CRU-73 style narrow panel regulator.
- Have students place their regulators in the OFF and NORMAL oxygen position.

NOTE: Students with new CRU-73 style regulator cannot perform this demonstration; they should drop their masks.

- As soon as they realize that they cannot breathe with regulator in this configuration, have them drop mask from right side of face.
- Have students with new style (CRU-73) regulators place their regulator in the OFF and NORMAL position.
- With this style regulator, it is impossible to breathe until you turn regulator to ON position. Have students experience this then remove mask from right side of face.

- At conclusion of demonstration, ensure that students understand the importance of postflighting any narrow panel regulator in the 100% and OFF configuration.

CONCLUSION OF CHAMBER FLIGHT:

- Instruct them to remain ahead of their ears and sinuses as chamber continues towards ground level.
- Instruct students to remain on intercom until reaching ground level.
- Remind students of “postflight” briefing immediately following flight.

POSTFLIGHT CONSIDERATIONS:

The primary concerns for students and inside observers following exposure to reduced barometric pressure are decompression sickness and ear problems. To minimize potential problems, all crew and students should follow the guidance provided as part of the postflight briefing, including:

- No physical exercise, strenuous activity, or extended duty for 12 hr.
- Personnel may fly as crew or passengers after a chamber flight to or below FL250 as long as cabin altitude remains below 15,000 ft.
- No flying as crew for 12 hr if chamber flight exceeded FL250. Personnel may fly as passengers if cabin altitude remains below 10,000 ft.
- Perform periodic Valsalvas throughout the day/evening to prevent delayed ear blocks.
- Minimize consumption of alcohol for 12 hr after a hypobaric exposure. Alcohol may mask the symptoms of DCS. Increased dehydration can increase DCS risk.
- Monitor your fatigue level. If possible, do not drive great distances without proper rest, use the buddy system, and take frequent breaks.

References

Air Force Instruction 11-202 volume 3, General Flight Rules. 22Oct2010.
Air Force Instruction 11-403, Aerospace and Operational Physiology Program. 20Feb2001.

Vocabulary

PRICE CHECK
Passenger oxygen kit (POK)
Personal breathing device (PBD)
Reduced oxygen breathing device (ROBD)

9. GLOSSARY

Absolute altitude	see AGL
Absolute pressure	Gauge pressure + local atmospheric pressure
AC	Aircraft Commander
ACC	Air Combat Command
ACCES	Attenuating Custom Communications Earpiece System
Acclimatization	The adjustments of a human body or other organism to a new environment; the bodily changes that tend to increase efficiency and reduce energy loss.
ACPM	American College of Preventive Medicine
AEF	Aerospace Expeditionary Force
Aero-otitis media	An inflammatory reaction of the middle ear resulting from a difference in pressure between the gas in the middle ear and the surrounding atmosphere. Also called otitic barotraumas.
Aerospace medicine	That branch of medicine dealing with the effects of flight through the atmosphere or in space upon the human body and with the prevention or cure of physiological or psychological malfunctions arising from these effects.
Aerospace	(From aeronautics and space). 1. Of or pertaining to both the Earth's atmosphere and space, as in aerospace industries. 2. Earth's envelope of air and space above it; the two considered as a single realm for activity in the flight of air vehicles and in the launching, guidance, and control of ballistic missiles, earth satellites, dirigible space vehicles, and the like. Used primarily by the U.S. Air Force. The term aerospace first appeared in print in the Interim Glossary; Aero-Space Terms (edited by Woodford Agee Heflin), published in February 1958 at the Air University, Maxwell Air Force Base, Alabama.
AETC	Air Education and Training Command
AF	Air Force
AFB	Air Force Base
AFFSA	Air Force Flight Standards Agency
AFMOA	Air Force Medical Operations Agency
AFRL	Air Force Research Laboratory
AFTO	Air Force Technical Order
AGL	Above Ground Level, height above the ground; also referred to as absolute altitude
AGSM	Anti-G straining maneuver
AHFA	Aerospace Human Factors Association

AIM	Aeronautical Information Manual
Altitude	The vertical distance of a level, a point, or an object considered as a point, measured from a reference point, usually taken to be mean sea level (MSL)
AMDS	Aerospace Medicine Squadron
AOA	Angle of attack
APA	Aerospace Physiology Apprentice
APA	American Psychiatric Association
APC	Aerospace Physiology Craftsman
APIMS	Aerospace Physiology Information Management System
APO	Aerospace Physiology Officer
APPB	Assisted Positive Pressure Breathing for Altitude
APTF	Aerospace Physiology Training Flight
AsMA	Aerospace Medical Association
ATC	Air Traffic Control
ATD	Aircrew Training Device
ATIS	Air Terminal Information System
atm	Atmosphere, pressure at Earth's surface is nominally one atmosphere (1 atm); but varies slightly depending on the weather conditions.
BIC	Basic Instructor Course
C2	Command and Control
C3	Command, Control, and Communications
C3I	Command, Control, Communications, and Information
CAS	Close Air Support
CATM	Curriculum, Administration, Training, Management
CCAF	Community College of the Air Force
CDC	Career Development Course
CDI	Course Deviation Indicator
CFETP	Career Field Enlisted Training Program
CINC	Commander-in-Chief
Communication	The act of sharing information with others to cause some kind of action: to direct, to inform, to question, or to persuade.
CONOPs	Concept of Operations
CONUS	Continental United States

Crew Coordination	As used in this instruction, the act of working with all the members of the crew to accomplish the tasks of the mission.
Crew	As used in this instruction, any collection of Air Force personnel who routinely work together to accomplish an Air Force mission. For example, an air task order-designated team of fighter pilots and airborne battle managers prosecuting an interdiction mission uses "crew" skills to maximize its effectiveness.
CRM	Cockpit/Crew Resource Management. The effective use of all available resources--people, weapon systems, facilities, and equipment, and environment--by individuals or crews to safely and efficiently accomplish an assigned mission or task. The term “CRM” will be used to refer to the training program, objectives, and key skills directed to this end. MAJCOMs may implement their programs as either “cockpit” or “crew” resource management based on their respective missions.
CSW	Course Selector Window
CTS	Course Training Standards
CWS	Cockpit Warning System
dB	Decibel, unit of sound intensity
DCI	Decompression Illness; general term encompassing all pathological changes secondary to reduction of environmental pressure; includes DCS, embolism, ebullism, trapped gas, hypoxia, anoxia.
DCS	Decompression Sickness; symptoms caused by nitrogen gas dissolved in body fluids and tissues forming a gas phase during decompression and interacting with nervous tissue and blocking blood flow.
Decision Making	The ability to choose a course of action using logical and sound judgment based on available information.
Dew Point	The point at which the air at a certain temperature contains all the moisture possible without precipitation occurring. When the dew point is 65 ^{o}F, one begins to feel the humidity. The higher the temperature associated with the dew point, the more uncomfortable one feels.
DME	Distance Measuring Equipment
DNIF	Duty Not Including Flying
DoD	Department of Defense
DR	Dead Reckoning
DRU	Direct Reporting Unit
DT&E	Development, Test, and Evaluation

EADI	Electronic Attitude Director Indicator
Ebullism	The vaporization of body water above Armstrong's Line, 63,000 ft, where the vapor pressure of water is equal to the ambient pressure, 47 mmHg.
ECM	Electronic Countermeasures
ECS	Environmental Control System
EPT	Effective Performance Time; relates to time from exposure to hypoxic conditions to loss of effective performance.
EFIS	Electronic Flight Instrument System
EHF	Extremely High Frequency
EHSI	Electronic Horizontal Situation Indicator
ELP	Emergency Landing Pattern
Embolism	The transfer of gas from the lung to the circulatory system resulting from excessive transthoracic pressure.
EP	Emergency Procedures
Exercise	Considered synonymous with physical activity in the past, but more recently, exercise denotes a subcategory of physical activity. Exercise, a type of physical activity, is defined as a planned, structured, and repetitive bodily movement done to improve or maintain one or more components of physical fitness. Physical activity performed for the sole purpose of enhancing physical fitness.
Exercise Training	Repetitive bouts of exercise conducted over periods of weeks or months with the intention of developing physical or physiological fitness. General types of exercise training: cardiorespiratory endurance (aerobic), muscular strength and endurance (resistance, plyometric, etc.), athletic or performance physical fitness training = combination of health- and skill-related physical fitness components.
Exercise Physiology	Exercise science/physiology, the parent discipline, is the study of body function. Exercise physiology is the study of how the body's structures and functions adapt physiologically to the perturbation of exercise, both the acute stress of physical activity/exercise and the chronic stress of physical training.
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAR	Federal Aviation Regulation(s)
FCIF	Flight Crew Information File
FL	Flight Lead

FL	Flight Level; hundreds of feet; used to indicate altitude by pilots and flight controllers, typically at 18,000 ft (FL180) and above.
Flight Discipline	The judgment and actions exercised by AF personnel to adhere to the spirit, intent, and written word of governing guidelines in the presence of temptation to do otherwise while executing the Air Force flying mission. It also includes the prioritization of tasks based on crew responsibilities to ensure safe mission accomplishment while demonstrating the highest degree of integrity in the performance of flight duties.
Flight Integrity	Utilizing all the members of a flying package to accomplish the mission at hand.
FLIP	Flight Information Publications
FLIR	Forward Looking Infrared systems
FOA	Field Operating Agency
FOD	Foreign Object Damage
fpm	feet per minute
FS	Flight Surgeon
FSA	Future Strike Aircraft
G or g	Acceleration of gravity. The standard value of gravity, or normal gravity, g, is defined as g_o=980.665 centimeters per second squared, or 32.1741 feet per second squared.
Geometric altitude	The scale we are most familiar with; it is the altitude we would measure with a tape measure.
GLOC	G-induced Loss of Consciousness
GMT	Greenwich Mean Time; same as Zulu time
GPS	Global Positioning System
GSTF	Global Strike Task Force
GWOT	Global War on Terrorism
HAAMS	High Altitude Airdrop Mission Support
HAHO	High Altitude High Opening
HALO	High Altitude Low Opening
HAMS	High Altitude Mission Support
HAP	High Altitude Parachutists
HARMS	High Altitude Reconnaissance Mission Support
HATR	Hazardous Air Traffic Report
Health	A human condition with physical, social, and psychological dimensions, each characterized on a continuum with positive

	and negative poles. Positive health is associated with a capacity to enjoy life and to withstand challenges; it is not merely the absence of disease. Negative health is associated with morbidity and, in the extreme, premature mortality.
HFACS	DoD Human Factors Analysis and Classification System
HMD	Helmet-Mounted Display
hPa	hectoPascals, or hundreds of Pascals (newtons per square meter, the metric unit of pressure); the preferred unit for atmospheric science. Standard atmospheric pressure is 1013.25 hPa (29.92 inches of Hg; 1013.25 mb).
HPE	Human Performance Enhancement
HPT	Human Performance Team
HPTT	Human Performance Training Team
HPW	Human Performance Wing (711th)
HSI	Human Systems Integration
HUD	Heads-Up Display
IAASM	International Academy of Aviation and Space Medicine
IAF	Initial Approach Fix
IAP	Instrument Approach Plates
ICAO	International Civil Aeronautical Organization; the international body governing the operation of commercial aircraft.
IFE	In-Flight Emergency
IFF	Identification, Friend or Foe (part of the aircraft transponder system)
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IMSAFE	Checklist on Self-Medication (see section 4.2.2)
inches Hg	Inches of Mercury, and the number given in most weather reports in the United States. Standard pressure is 29.92 inches Hg.
inches	Inches of water pressure. Used to describe mask pressure in some documents.
INS	Inertial Navigation System
IP	Instructor Pilot
IRB	Institutional Review Board

ITO	Instrument Takeoff
JA/ATT	Joint Airborne/Air Transportability Tasking
Jet Stream	Strong winds concentrated within a narrow zone in the atmosphere in the upper troposphere, about 30,000 ft aloft, that generally move in an easterly direction and drive weather systems around the globe. In North America, jet streams are more pronounced in winter.
JHMCS	Joint Helmet-Mounted Cueing System
JSUPT	Joint Specialized Undergraduate Pilot Training
KIAS	Knots Indicated Airspeed
KIO	Knock It Off (stop current operations immediately)
Kollsman window	The window in an altimeter where the altimeter setting in inches of Hg is displayed. Standard setting while flying above 18,000 ft is 29.92.
Lapse rate	The decrease of temperature with height, considered positive when temperature decreases with height.
LGB	Laser Guided Bomb
LOC	Loss of Consciousness
LOS	Line-of-Sight
LRSA	Long-Range Strike Aircraft
M (Mach)	Mach number. The Mach number is a ratio between the aircraft's speed, v, and the speed of sound, a; $M = v/a$.
MAJCOM	Major Command
MAX	Maximum thrust position
mb	Millibar or thousandths of a bar, where a bar is approximately the same as an atmosphere; 1mb = 1 hPa.
MC	Mission Capable
MDA	Minimum Descent Altitude
MEA	Minimum En Route Altitude. The altitude in effect between radio fixes that ensures acceptable navigational signal coverage and meets obstruction clearance requirements between those fixes.
Mission Debrief	Reviewing and discussing mission accomplishment looking at what was achieved, what barriers were encountered, and how the mission could be accomplished better next time.
Mission Planning	Taking all of the information for a mission and developing short-term, long-term, and contingency plans to coordinate, allocate, and monitor crew/flight and aircraft resources. Effective planning leads to flight conduct that removes

	uncertainty, increases mission effectiveness, and enhances safety.
mmHg	Millimeters of Mercury. Standard pressure is 760.0 mmHg.
MOA	Military Operations Area
MOCA	Minimum Obstruction Clearance Altitude. That specified altitude in effect between radio fixes on VOR airways, off-airway routes, or route segments that meets obstruction clearance requirements for the entire route segment and that ensures acceptable navigational signal coverage only within 22 nautical miles of a VOR.
MOST	Mission-Oriented Simulator Training. Training presented as a part of a CRM program in a realistic, operationally based simulator environment in real time.
MSL	Mean Sea Level, the height above
MTR	Military Training Route
Muscle Contraction	Muscle contraction has both mechanical and metabolic categories. Mechanical classification stresses whether the muscle contraction produces movement of the limb: Classification of Muscle Contraction: Isometric (same length) or static exercise where there is no movement of the limb Isotonic (same tension) or dynamic exercise if there is movement of the limb Isokinetic (same velocity) dynamic exercise contraction of constant torque or tension at a set speed at all points in the range of motion Metabolic classification involves the availability of oxygen for the contraction process and includes aerobic (oxygen available) or anaerobic (oxygen unavailable) processes. Whether an activity is aerobic or anaerobic depends primarily on its intensity. Most activities involve both static and dynamic contractions and aerobic and anaerobic metabolism. Thus, activities tend to be classified according to their dominant features. Contextual Classification: physical activity categorized by the context in which it occurs. Common categories include occupational, household, leisure time, and transportation. Leisure-time activity can be further subdivided into categories such as competitive sports, recreational activities, and exercise training.
NACWS	Naval Aircraft Collision Warning System
NASA	National Aeronautics and Space Administration

NAVAID	Navigational aid
NCA	National Command Authority
NCOIC	Noncommissioned Officer in Charge
nm	Nautical mile
NOAA	National Oceanic and Atmospheric Administration
NORDO	No radio
NOTAM	Notice to Airman
NTSB	National Transportation Safety Board
NVD	Night-Vision Device/s
NVG	Night-Vision Goggles
NWS	National Weather Service, http://www.nws.noaa.gov
OBOGS	Onboard Oxygen-Generating System
OIC	Officer-in-Charge
ORM	Operational Risk Management
Ozone	A molecule consisting of three oxygen atoms that is formed by a reaction of oxygen and ultraviolet radiation. In the stratosphere, ozone has beneficial properties: it forms an ozone shield that prevents dangerous radiation from reaching the Earth's surface. Closer to the planet's surface, ozone is considered an air pollutant that adversely affects humans, plants, and animals as well as acts like a greenhouse gas.
PA or Pressure Altitude	A type of geopotential height used so that aircraft, which use static pressure to determine altitude, can agree upon what "altitude" they are flying at without having to continually update their altimeters with local pressure corrections. Technically, this is only true above 18,000 ft (FL180). Altitude in the Earth's atmosphere above the standard datum plane, standard sea level pressure, measured by a pressure altimeter.
PACAF	Pacific Air Force
PAPI	Principles of Aerospace Physiology Instruction
Physical Activity	Bodily movement produced by the contraction of skeletal muscle that increases energy expenditure above the basal level. Health benefits increase with the intensity of the activity and the time you engage in it each week. Exercise is a type of regular physical activity that we perform to maintain or improve physical fitness. You can obtain health benefits from physical activity even if it does not increase your physical fitness level. Physical activity can be classified in various ways.

	Leisure-Time Physical Activity - one category of physical activity; physical activity that a person or group chooses to undertake during discretionary time.
Physical Fitness	Several general definitions:
	A set of attributes that people have or achieve that relates to the ability to perform physical activity.
	The ability to carry out daily tasks with vigor and alertness, without undue fatigue, and with ample energy to enjoy leisure-time pursuits and to meet unforeseen emergencies (President's Council on Physical Fitness and Sport).
	The ability to perform moderate to vigorous levels of physical activity without undue fatigue and the capability of maintaining such ability throughout life (ACSM).
	The ability to last, to bear up, to withstand stress, and to persevere under difficult circumstances when an unfit person would quit. The opposite to becoming fatigued from ordinary efforts; to lacking energy to enter zestfully into life's activities; and to becoming exhausted from unexpected, demanding physical exertion.
	The physical ability to meet the demands of your environment.
	These are some of the myriad definitions of physical fitness, but they are somewhat lacking in the means for objective, simple measurement. One must consider components of fitness for such.
Physical Inactivity	Lack of regular exercise. Physical inactivity denotes a level of activity less than that needed to maintain good health.
POI	Plan/s of Instruction
psi	Pounds per square inch, the standard unit used in the aeronautical industry in the United States. Standard atmospheric pressure is 14.7 psi.
psia	Pounds per square inch absolute; see Absolute pressure
PT	Physiology Technician
R&M	Reliability and Maintainability
RCR	Runway Condition Reading
RDT&E	Research, Development, Test, and Evaluation
RESCAP	Rescue combat air patrol
RH	Relative Humidity. The ratio of the ambient vapor pressure of water to the saturated vapor pressure at the particular temperature. It is usually calculated with respect to liquid water even when the temperature is below the melting point.

Risk Management	Logic-based, common sense approach to making calculated decisions on human, material, and environmental factors before, during, and after Air Force mission activities and operations, i.e., on- and off-the-job.
ROBD	Reduced Oxygen Breathing Device
ROBE	Reduced Oxygen Breathing Environment
rpm	Revolutions per minute
RSU	Runway Supervisory Unit
SA	Situational Awareness. In flying, this refers to an aircrew member's continuous perception of self and aircraft in relation to the dynamic environment of flight, threats, and mission and the ability to forecast, then execute, tasks based upon that perception.
SAAM	Special Assignment Air Mission
SATCOM	Satellite Communication
SCUBA	Self-Contained Underwater Breathing Apparatus
Sedentary Lifestyle	Synonymous with physical inactivity
SFL	Simulated Forced Landing
Signs	Evidence of disease; an indication of the presence of a disease or disorder, especially one observed by a doctor but not apparent to the patient.
SII	Special interest item
Skills Criteria	Defined skills used as the basis for operational training and evaluation. The characteristics of the skill are that they are easily identifiable and offer consistency in grading evaluation.
SLT	Swing Landing Training
SOF	Supervisor of Flying
SRB	Safety Review Board
Stratospheric ozone	In the stratosphere, ozone has beneficial properties: it forms an ozone shield that prevents dangerous radiation from reaching the Earth's surface. Recently, it was discovered that in certain parts of the world, especially over the poles, stratospheric ozone was disappearing, creating an ozone hole.
STS	Specialty Training Standard
Symptoms	Indication of illness felt by patient; an indication of a disease or other disorder, especially one experienced by the patient, e.g., pain, dizziness, or itching, as opposed to one observed by the doctor.

TACAN	TACtical Air Navigation
TCAS	Traffic Collision Avoidance System
TAS	True Airspeed
Task Management	The ability to alter a course of action based on new information, maintain constructive behavior under pressure, and adapt to internal and external environment changes.
TDY	Temporary Duty
TO	Technical Order
torr	This unit is named after the scientist Torricelli and is another name for mmHg; standard pressure in this unit is also 760.0 torr.
TUC	Time of Useful Consciousness; time of consciousness with the ability to take corrective action; now called Effective Performance Time (EPT).
UHF	Ultra High Frequency
UMD	Unit Manning Document
UMPR	Unit Personnel Management Roster
USAF	United States Air Force
USAFE	United States Air Forces in Europe
USAFSAM	USAF School of Aerospace Medicine
USUHS	Uniformed Services University of the Health Sciences
USSTRATCOM	United States Strategic Command
UTC	Universal Time Coordinated; substituted for GMT
UV	Ultraviolet radiation from the sun plays a role in the formation of the ozone layer by acting as a catalyst for a chemical reaction that breaks apart oxygen molecules which then recombine to form ozone. The absorption of UV by stratospheric ozone and atmospheric oxygen prevents very little ultraviolet radiation from reaching Earth's surfaces where it can have detrimental effects on human health and property.
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	Very high frequency omnidirectional range station
VORTAC	Very high frequency omnidirectional range station and TACtical air navigation
VSI	Vertical Speed Indicator
VVI	Vertical Velocity Indicator

Z or Zulu	Zulu (military and aviation) time; GMT

References

Internet Resources, See Appendix 8
http://physics.nist.gov/Pubs/SP811/appenB8.html

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Appendix 1a: Altitude of Exposure vs. Alveolar Partial Pressure of Oxygen – Sea Level to 45,000 ft Breathing Air

Alt (ft)	Alt (m)	Pressure (psi)	Pressure (mb)	PB (mmHg)	$PACO_2$ (mmHg)	R	PTO_2 (mmHg)	PAO_2 (mmHg)	Temp (°C)	%Hb Sat	EPT (min)
0	0	14.70	1013.3	760.0	40.0	0.85	149.7	104.2	15.0	97[1],97[2]	
1,000	305	14.17	977.2	732.9	39.5	0.85	144.0	99.2	13.0		
2,000	610	13.67	942.1	706.7	39.0	0.86	138.5	94.4	11.0		
3,000	914	13.17	908.1	681.2	38.5	0.86	133.2	89.8	9.1		
4,000	1,219	12.69	875.1	656.4	38.0	0.87	128.0	85.3	7.1	94[2]	
5,000	1,524	12.23	843.1	632.4	37.5	0.87	122.9	81.0	5.1		
6,000	1,829	11.78	812.0	609.1	37.0	0.88	118.0	76.9	3.1		
7,000	2,134	11.34	781.9	586.5	36.5	0.88	113.3	72.9	1.1	91[2]	
8,000	2,438	10.92	752.7	564.6	36.0	0.89	108.7	69.1	-0.8	93[1]	
9,000	2,743	10.51	724.4	543.3	35.5	0.89	104.2	65.4	-2.8		
10,000	3,048	10.11	696.9	522.7	35.0	0.90	99.9	61.8	-4.8		
11,000	3,353	9.72	670.3	502.8	34.4	0.91	95.7	58.6	-6.8	86[2]	
12,000	3,658	9.35	644.6	483.5	33.8	0.92	91.7	55.5	-8.8	84[1]	
13,000	3,962	8.99	619.6	464.8	33.2	0.93	87.7	52.6	-10.7		
14,000	4,267	8.64	595.5	446.6	32.6	0.94	83.9	49.7	-12.7		
15,000	4,572	8.30	572.1	429.1	32.0	0.95	80.2	46.9	-14.7	78[1],75[2]	
16,000	4,877	7.97	549.4	412.1	31.5	0.96	76.7	44.1	-16.7		
17,000	5,182	7.65	527.5	395.7	31.0	0.97	73.2	41.5	-18.7		
18,000	5,486	7.35	506.3	379.8	30.4	0.98	69.9	39.0	-20.6	72[1]	
19,000	5,791	7.05	485.8	364.4	29.9	0.99	66.7	36.5	-22.6	68[2]	
20,000	6,096	6.76	466.0	349.5	29.4	1.00	63.5	34.1	-24.6	66[1]	20-30[3]
21,000	6,401	6.48	446.8	335.2	28.9	1.02	60.5	32.0	-26.6		
22,000	6,706	6.21	428.3	321.3	28.4	1.03	57.6	29.9	-28.5	68[1]	10[3]
23,000	7,010	5.95	410.5	307.9	27.9	1.05	54.8	27.8	-30.5		
24,000	7,315	5.70	393.2	294.9	27.4	1.06	52.1	25.9	-32.5	56[2]	
25,000	7,620	5.46	376.5	282.4	27.0	1.08	49.4	24.0	-34.5		3-5[3]
26,000	7,925	5.23	360.4	270.3	26.6	1.08	46.9	21.8	-36.4		
27,000	8,230	5.00	344.9	258.7	26.2	1.09	44.5	19.9	-38.4		
28,000	8,534	4.78	329.9	247.4	25.8	1.09	42.1	18.0	-40.4		2.5-3[3]
29,000	8,839	4.58	315.4	236.6	25.4	1.10	39.8	16.2	-42.4		
30,000	9,144	4.37	301.5	226.1	25.0	1.10	37.6	14.4	-44.4		1-2[3]
31,000	9,449	4.18	288.1	216.1	24.6	1.11	35.5	12.8	-46.3		
32,000	9,754	3.99	275.1	206.3	24.2	1.11	33.5	11.1	-48.3		
33,000	10,058	3.81	262.6	197.0	23.8	1.12	31.5	9.6	-50.3		
34,000	10,363	3.64	250.6	188.0	23.4	1.12	29.6	8.2	-52.3		
35,000	10,668	3.47	239.1	179.3	23.0	1.13	27.8	6.8	-54.2		0.5-1[3]
36,000	10,973	3.31	228.0	171.0	22.6	1.13	26.0	5.5	-56.5		
37,000	11,278	3.15	217.3	163.0	22.2	1.14	24.4	4.2	-56.5		
38,000	11,582	3.01	207.1	155.4	21.8	1.14	22.8	3.1	-56.5		
39,000	11,887	2.86	197.5	148.1	21.4	1.15	21.2	2.0	-56.5		
40,000	12,192	2.73	188.2	141.2	21.0	1.15	19.8	0.9	-56.5		0.25-0.33[3]
41,000	12,497	2.60	179.4	134.6	20.6	1.16	18.4	0.0	-56.5		
42,000	12,802	2.48	171.0	128.3	20.2	1.16	17.1	-0.9	-56.5		
43,000	13,106	2.37	163.0	122.3	19.8	1.17	15.8	-1.8	-56.5		
44,000	13,411	2.26	155.4	116.6	19.4	1.17	14.6	-2.6	-56.5		
45,000	13,716	2.15	148.2	111.1	19.0	1.18	13.5	-3.3	-56.5		0.15-0.20[3]

Appendix 1b: Altitude of Exposure vs. Alveolar Partial Pressure of Oxygen – 25,000 to 50,000 ft Breathing 100% O_2 + PBA

Alt (ft)	Alt (m)	Pressure (psi)	Pressure (mb)	P_B (mmHg)	$PACO_2$ (mmHg)	R	PTO_2 (mmHg)	PAO_2 (mmHg)	Temp (°C)	%Hb Sat	PBA (mmHg)
25,000	7,620	5.46	376.5	282.4	40.0	1.00	235.4	195.4	-34.5		
26,000	7,925	5.23	360.4	270.3	40.0	1.00	223.3	183.3	-36.4		
27,000	8,230	5.00	344.9	258.7	40.0	1.00	211.7	171.7	-38.4		
28,000	8,534	4.78	329.9	247.4	40.0	1.00	200.4	160.4	-40.4		
29,000	8,839	4.58	315.4	236.6	40.0	1.00	189.6	149.6	-42.4		
30,000	9,144	4.37	301.5	226.1	40.0	1.00	179.3	139.3	-44.4		
31,000	9,449	4.18	288.1	216.1	39.2	1.00	169.3	130.1	-46.3		
32,000	9,754	3.99	275.1	206.3	38.4	1.00	159.5	121.1	-48.3		0.02
33,000	10,058	3.81	262.6	197.0	37.6	1.00	150.2	112.6	-50.3	97[1]	
34,000	10,363	3.64	250.6	188.0	36.8	1.00	141.2	104.4	-52.3		0.02
35,000	10,668	3.47	239.1	179.3	36.0	1.00	132.5	96.5	-54.2		
36,000	10,973	3.31	228.0	171.0	35.5	1.00	124.2	88.7	-56.5		0.02
37,000	11,278	3.15	217.3	163.0	35.0	1.00	116.2	81.2	-56.5		
38,000	11,582	3.01	207.1	155.4	34.5	1.00	108.6	74.1	-56.5		0.02
39,000	11,887	2.86	197.5	148.1	34.0	1.00	101.3	67.3	-56.5		0.02
40,000	12,192	2.73	188.2	141.2	33.5	1.00	94.3	60.8	-56.5	84[1]	0.06
41,000	12,497	2.60	179.4	134.6	32.0	1.00	90.6	58.6	-56.5		3.0
42,000	12,802	2.48	171.0	128.3	31.0	1.00	87.7	56.7	-56.5		6.4
43,000	13,106	2.37	163.0	122.3	30.0	1.00	82.8	52.8	-56.5	76[1]	7.5
44,000	13,411	2.26	155.4	116.6	30.0	1.00	77.1	47.1	-56.5		
45,000	13,716	2.15	148.2	111.1	30.0	1.00	79.0	49.0	-56.5		14.9
46,000	14,021	2.05	141.2	105.9	30.0	1.00	73.8	43.8	-56.5		
47,000	14,326	1.95	134.6	101.0	30.0	1.00	75.0	45.0	-56.5		21.0
48,000	14,630	1.86	128.4	96.3	30.0	1.00	71.7	41.7	-56.5		22.4
49,000	14,935	1.78	122.4	91.8	30.0	1.00	67.2	37.2	-56.5		
50,000	15,240	1.69	116.6	87.5	30.0	1.00	68.3	38.3	-56.5		27.8

Altitudes shown in Appendix 1 are geometric altitude; U.S. Standard Atmosphere

Notes for Appendix 1a:

- EPT (effective performance time) = maximum time the crewmember has to make rational, life-saving decisions and carry them out at a given altitude without supplemental oxygen.

Notes for Appendices 1b & 1c:

- The levels of additional pressure from PBA are included in the **PT**O_2 column; 1 mmHg = 1 torr; **PA**O_2 values are for acute exposure during rest.
- The values for minimum positive pressure for altitude (PBA) were obtained for two oxygen regulators, which deliver within 2.5 mmHg of the same pressure at any comparable altitude in the specifications.
- **CRU 93**: Lockheed Martin Amendment No. 2 (28 Oct 1996) to Specification 16ZK048D dated 1 Oct 1990 for F-15 and F-16 PBG at 10 L/min ambient flow [Table II; Sheet 15 Rev D, SP1638050].
- **CRU 98**: MSOC-specific F-15-E PBG at 10 L/min ambient flow [Table IV; Sheet 10 Rev. H, SD1638058].
- **BRAG**: Data not available as of 12 Dec 06 for FA-22.

Appendix 1c: Altitude of Exposure vs. Alveolar Partial Pressure of Oxygen – 50,000 to 70,000 ft Breathing 100% O2 + PBA

Alt (ft)	Alt (m)	Pressure (psi)	Pressure (mb)	PB (mmHg)	$PACO_2$ (mmHg)	R	PTO_2 (mmHg)	PAO_2 (mmHg)	Temp (°C)	PBA[a] (mmHg)
50,000	15,240	1.69	116.6	87.5	30.0	1.00	70.5	40.5	-56.5	27.8
51,000	15,545	1.61	111.2	83.4	30.0	1.00	66.3	36.3	-56.5	29.9
52,000	15,850	1.54	106.0	79.5	30.0	1.00	62.4	32.4	-56.5	29.9
53,000	16,154	1.47	101.1	75.8	30.0	1.00	58.7	28.7	-56.5	29.9
54,000	16,459	1.40	96.3	72.3	30.0	1.00	55.2	25.2	-56.5	29.9
55,000	16,764	1.33	91.8	68.9	30.0	1.00	51.8	21.8	-56.5	29.9
56,000	17,069	1.27	87.5	65.7	30.0	1.00	48.6	18.6	-56.5	29.9
57,000	17,374	1.21	83.5	62.6	30.0	1.00	45.5	15.5	-56.5	29.9
58,000	17,678	1.15	79.6	59.7	30.0	1.00	42.6	12.6	-56.5	29.9
59,000	17,983	1.10	75.9	56.9	30.0	1.00	39.8	9.8	-56.5	29.9
60,000	18,288	1.05	72.3	54.2	30.0	1.00	37.1	63[b]	-56.5	70[b]
61,000	18,593	1.00	68.9	51.7	29.5	1.01	34.6	5.1	-56.5	29.9
62,000	18,898	0.95	65.7	49.3	29.0	1.02	32.2	3.2	-56.5	29.9
63,000	19,202	0.91	62.7	47.0	28.5	1.03	29.9	1.4	-56.5	29.9
64,000	19,507	0.87	59.7	44.8	28.0	1.04	27.7	-0.3	-56.5	29.9
65,000	19,812	0.83	56.9	42.7	27.5	1.05	25.6	-1.9	-56.5	29.9
66,000	20,117	0.79	54.3	40.7	27.0	1.06	23.6	-3.4	-56.4	29.9
67,000	20,422	0.75	51.8	38.8	26.5	1.07	21.7	-4.8	-56.1	29.9
68,000	20,726	0.72	49.4	37.0	26.0	1.08	19.9	-6.1	-55.8	29.9
69,000	21,031	0.68	47.1	35.3	25.5	1.09	18.2	-7.3	-55.5	29.9
70,000	21,336	0.65	44.9	33.7	25.0	1.00	16.6	-8.4	-55.2	29.9

[a]Based on CRU-93 and CRU-98 oxygen regulators.
[b]Personal communication; Gp Capt David Gradwell, M.D.

FIO_2, fraction of the total pressure which is oxygen; breathing air = 0.21; breathing 100% oxygen = 1.0 (not shown)
PB, barometric pressure in mmHg
PH_2O, water vapor pressure at body temperature, a constant 47 mmHg (not shown)
$PACO_2$, partial pressure of carbon dioxide in the alveoli, 40 mmHg at sea level.
PTO_2, calculated partial pressure of oxygen in the trachea
PAO_2, calculated partial pressure of oxygen in the alveoli

http://www.faa.gov/library/manuals/aviation/pilot_handbook/media/faa-h-8083-25-4of4.pdf (FAA-H-8083-25-1)
http://www.faa.gov/pilots/training/airman_education/media/AC%2061-107A.pdf [87% @ 12K]
http://history.nasa.gov/SP-4701/session%201.pdf [65% @ 20K]
http://www.usaisr.amedd.army.mil/ewsh/Chp4AeroMed.pdf [98-100% at SL; 90% @ 8K]
http://www.alma.nrao.edu/memos/html-memos/alma162/memo162.html [87-95% @ 8K; 81-88% @ 12K; 71-85% @ 15K; 65-83% @ 17K; 56-73% @ 19.5K]

References

1 Ernsting & King. Aviation Medicine, 2nd Ed. 1988.
2 Lambertsen CJ, PL Bunce, DL Drabkin and CF Schmidt. Relationship of oxygen tension to hemoglobin oxygen saturation in the arterial blood of normal men. J. Appl. Physiol. 4(12): 873-885, 1952.
3 Davis JR, Johnson R, Stepanek J, Fogarty JA, Eds. Fundamentals of Aerospace Medicine. 4th Ed. Lippincott Williams & Wilkins. 2008.

Appendix 2a: Unit Conversion Table; Linear Units

One	cm	in.	ft	m	km	mi	nm
Centimeter (cm) =	1	0.3937	3.280 X 10^{-2}	1.000 X 10^{-2}	1.000 X 10^{-5}	6.215 X 10^{-6}	5.300 X 10^{-6}
Inch (in) =	2.540	1	8.333 X 10^{-2}	2.540 X 10^{-2}	2.540 X 10^{-5}	1.578 X 10^{-5}	1.371 X 10^{-5}
Foot (ft) =	30.48	12.0	1	0.3048	3.048 X 10^{-4}	1.894 X 10^{-4}	1.646 X 10^{-4}
Meter (m) =	1.000 X 10^{2}	39.37	3.281	1	1.000 X 10^{-3}	6.214 X 10^{-4}	5.402 X 10^{-4}
Kilometer (km) =	1.000 X 10^{5}	3.937 X 10^{4}	3.281 X 10^{3}	1000	1	0.6214	0.5396
Statute Mile (mi) =	1.609 X 10^{5}	6.336 X 10^{4}	5.280 X 10^{3}	1.609 X 10^{3}	1.609	1	0.8684
Nautical mile (nm) =	1.852 X 10^{5}	7.291 X 10^{4}	6.076 X 10^{3}	1.851 X 10^{3}	1.853	1.152	1

Appendix 2b: Unit Conversion Table; Pressure Units

One	atm	N/m^2	kg/cm^2	g/cm^2	psi	bars	mb or hPa	mmHg	in. Hg	in. H_2O
atm =	1	1.013 X 10^{5}	1.033	1.033 X 10^{3}	14.70	1.013	1.013 X 10^{3}	7.600 X 10^{2}	29.92	4.067 X 10^{2}
Newton/m^2 =	9.872 X 10^{-6}	1	1.020 X 10^{-5}	1.020 X 10^{-2}	1.452 X 10^{-4}	1.000 X 10^{-5}	1.000 X 10^{-2}	7.501 X 10-3	2.953 X 10^{-4}	4.014 X 10^{-3}
kg/cm^2 =	0.9681	9.807 X 10^{4}	1	1.000 X 10^{3}	14.22	0.9807	9.807 X 10^{2}	7.356 X 10^{2}	28.94	3.937 X 10^{2}
g/cm^2 =	9.681 X 10^{-4}	98.07	1.000 X 10^{-3}	1	0.01422	9.807 X 10^{-4}	0.9807	0.7356	2.894 X 10^{-2}	0.3937
psi =	6.803 X 10^{-2}	6.895 X 10^{3}	7.030 X 10^{-2}	70.3	1	6.895 X 10^{-2}	68.95	51.72	2.036	27.67
bar =	0.9869	1.000 X 10^{5}	1.019	1.019 X 10^{3}	14.50	1	1.000 X 10^{3}	7.501 X 10^{2}	29.53	4.014 X 10^{2}
mb or hPa =	9.869 X 10^{-4}	1.000 X 10^{2}	1.019 X 10^{-3}	1.020	1.450 X 10^{-2}	1.000 X 10^{-3}	1	0.7501	2.953 X 10^{-2}	0.4014
mmHg =	1.316 X 10^{-3}	1.333 X 10^{2}	1.360 X 10^{-3}	1.360	1.934 X 10^{-2}	1.333 X 10^{-3}	1.333	1	3.937 X 10^{-2}	0.5352
in. Hg =	3.342 X 10^{-2}	3.386 X 10^{3}	3.453 X 10^{-2}	34.55	0.4912	3.386 X 10^{-2}	33.86	25.4	1	13.60
in. H_2O =	2.459 X 10^{-3}	2.491 X 10^{2}	2.540 X 10^{-3}	2.54	3.614 X 10^{-2}	2.491 X 10^{-3}	2.49	1.868	7.355 X 10^{-2}	1

atm = atmosphere; N/m^2 = Newton/m^2 = Pascal = Pa = 10^5 dynes/cm^2; psi = lb/in.^{2}
mb = millibar = hPa = hectoPascals = 0.1 kPa = 1000 dynes/cm^2
g/cm^2 = cm H_2O since 1 cm^3 of water weighs very close to 1 g
Density of air at sea level is 1.229 kg/m^3
Fahrenheit to Celsius: °F –32 X 5/9 = °C
Celsius to Fahrenheit: °C * 9/5 + 32 = °F

Appendix 3: Prebreathe Requirements

AFI 11-409 (1 Dec 99, Certified Current 1 Feb 2011) Table 2.1. Prebreathing Requirements and Exposure Limits for High Altitude Operations

Altitude	Prebreathing Times (min)		Maximum Exposure Time Per Sortie (min)	Maximum Sorties Per 24-hr Period
	Aircrew	Jumpers		
From FL200 to FL249	30	30	110	3
From FL250 to FL299	30	30	60	3
From FL300 to FL349	45	45	30	3
FL350 or above	75	75	30	3

Appendix 4: Checklists

A. Checklist for Treatment of Hypoxia and Hyperventilation

1. All 3 switches up - <u>On</u> - <u>100% Oxygen</u> - <u>Emergency</u>
2. Mask - ON
3. Check regulator and connections
4. Control rate and depth of breathing
5. Notify aircraft commander, lead, or other flight members

B. Checklist for Treatment of Ear and Sinus Pain on Descent

1. Level off and try a Valsalva
2. Climb to relieve pressure
3. Try a Valsalva and decrease descent rate
4. Consider using Afrin or other vasoconstrictor
5. Declare an IFE?
6. Land as soon as practical

C. Checklist for Treatment of Ear and Sinus Pain on Ascent

1. DESCEND!!
2. Land as soon as practical

D. Checklist for Treatment of Tooth Pain

1. Descend and see Flight Surgeon/Dentist

E. Checklist for Treatment of GI Tract Pain

1. Release the gas and/or descend

F. Checklist for Treatment of DCS

1. 100% oxygen[3]
2. Descend as soon as practical
3. Declare IFE
4. Land at the nearest airfield with qualified medical assistance available

[3] Remain on 100% oxygen after landing, <u>especially</u> if symptoms are still present.

Appendix 5: USAF and Other FAA Directives Relevant to Aerospace Physiology

AETCI 11-406	Flying Operations: Fighter Aircrew Conditioning Program (FACP)
AETCI 36-2223	Flying Training Student Information Management
AFH 11-203v1&2	Weather for Aircrews
AFI 10-248	Fitness Program
AFI 11-202v3	General Flight Rules
AFI 11-217v1&2	Instrument Flight Procedures
AFI 11-290	Cockpit/Crew Resource Management Training Program
AFI 11-401	Aviation Management
AFI 11-403	Aerospace Physiological Training Program
AFI 11-403Sup1	Aerospace Physiological Training Program, AETC
AFI 11-404	Centrifuge Training for High-G Aircrew
AFI 11-409	High Altitude Airdrop Mission Support Program
AFI 11-409	High Altitude Airdrop Mission Support Program
AFI 11-419	G-Awareness for Aircrew
AFI 41-105	Medical Training Programs
AFI 41-120	Medical Resource Operations
AFI 41-209	Medical Logistics Support
AFI 48-123v1-4	Medical Examinations and Standards
AFJI 41-204	Joint Field Operating Agencies of the Surgeon General of the Army
AFMAN 10-100	Airman's Manual
AFMAN11-248	T-6 Primary Flying
AFMCI 11-206	Mobility Force Management
AL-TR-1993-0022	Spatial Orientation in Flight

Federal Aviation Regulation PART 91--General Operating and Flight Rules
Federal Aviation Regulation PART 121--Operating Requirements: Domestic, Flag, and Supplemental Operations

ICAO Human Factors Training Manual. 1998. Doc 9683-AN/950.
ICAO Training of Operational Personnel in Human Factors.
ICAO Human factors Digest No. 2. ICAO Circular 217-AN/132. 1989.
Guidance Notes for Accreditation Standards for CRM Instructors & CRM Examiners: Standards Document 29, version 1. 2001.
Human Factors Digest No 3. ICAO Circular 227-AN/136. 1991
Flight Crew Training: Cockpit Resource Management (CRM) and Line-Oriented Flight Training (LOFT).
Carver, T. Training and Maintaining Basic Airmanship Skills. Flight Safety Foundation. 10th EASS "Managing Aviation Safety — Back to Basics." Netherlands. March 1998
Briefings: A Human Factors Course for Pilots — Reference Manual and videos. 2000. Publishers Dédale, France.
ISBN 2-9509979-0-2 http://www.dedale.net/page_bfgs.html

Appendix 6: Physiology Demonstrations

Practical demonstrations of physiologic principles often provide a mechanism of learning that is very effective and can lead to better retention than a recitation of the facts involved. The following examples can be tailored to an individual's style of presentation.

Barany Chair Demonstrations

SSgt Blake Lapp and SSgt Shawn Rose

1. **Nystagmus-** This is a voluntary movement of the eyes caused by stimulation of any one of the semicircular canals. When the canals respond to rotation in one direction, the eyes tend to sweep slowly in the opposite direction and then jerk to the center position. The canal that is affected will determine which way the eyes move (up, right, etc.)

Check Instruments

- Have student sit upright in chair (Fig A6-1)
- Eyes closed
- Rotate chair for approximately 20-30 s
- Have three other students stand in front of where the chair will stop to act as "instruments" with different numbers held up with their fingers
- After 20-30 s stop chair and have student open eyes
- Student should try to cross check "instruments"

Read Something

- Have student sit upright in chair
- Eyes open
- Rotate chair for approximately 20-30 s
- Have student "track" stationary object
- Stop chair
- Have student try to read something

Graveyard Spin- When a turn is initiated, the fluid in the semicircular canals tends to lag behind and causes the hair cells to bend. The bending of the hair cells is what causes the sensation of turning. If you stay in the turn long enough, then the fluid will "catch up" with the canal and the hair cells will no longer bend. If the turn is stopped, the fluid continues to move and bends the hairs once again. This is what gives the student the false sensation of turning.

Figure A6-1. The Barany Chair

Indicate Turn Direction

- Have student sit upright in chair
- Place goggles and earmuffs on student
- The room must remain as quiet as possible during this demonstration
- The student will indicate the direction of the turn with his/her thumbs (Fig A6-2)
- Rotate the chair as smoothly as possible as the student indicates the direction
- Continue to rotate until fluid reaches equilibrium (approximately 20-30 s) – the student should point thumbs in up position indicating no turning sensation
- Slow the turn enough to let the student feel the change or abruptly stop the chair and student should indicate thumbs in the opposite direction of the actual initial turn

Figure A6-2. Graveyard Spin Illusion

2. **Coriolis -** This illusion occurs when there is a stimulation of two or more semicircular canals that gives the false sense of rotation in the third canal. The result is a tumbling sensation.

Leans

- Have student sit with head forward on the arms, resting on the bar
- Keep eyes closed throughout the entire demonstration
- Rotate until fluid reaches equilibrium (student senses no turn)
- Stop the chair, have student sit upright and throw arms up overhead in a “touchdown” fashion, eyes still closed
- Student will lean in direction of turn (Fig A6-3)

Double Axis

- Have student sit with head forward on the arms, with face turned to one side
- Keep eyes closed throughout entire demonstration
- Rotate chair until equilibrium is reached
- Stop the chair and have student sit upright and point at a fixed object
- Student should react as follows:
  - Right ear down, rotate toward face: **Movement: forward/right**
  - Right ear down, rotate opposite face: **Movement: backward/right**
  - Left ear down, rotate toward face: **Movement: forward/left**
  - Left ear down, rotate opposite face: **Movement: backward/left**

Figure A6-3. Coriolis Illusion

3. Other Demonstrations

Disorientation 1

- Have student sit upright with eyes closed and arms crossed on chest
- Rotate the chair until equilibrium is reached
- Have student touch chin to chest, right ear to right shoulder, left ear to left shoulder, look right, look left, tilt head back, rest forehead on arms on the bar
- Keep eyes closed throughout entire demonstration
- Have student describe sensation of direction during each movement

Disorientation 2

- Have student sit with thead down and turned to one side on the arms, resting on the bar
- Rotate the chair until equilibrium is reached
- Have student lift head and put other ear down on bar
- Repeat if comfortable
- Stop chair and have the student raise arms overhead in a “touchdown” fashion with eyes opened or closed

NOTE: *Ensure that seat belt is fastened during all demonstrations. Make sure someone is available to assist the student if needed. Allow the student time in the seat before sitting up to prevent falling out. Normal rotation speed for the chair is 25-30 rotations per minute.*

Appendix 7: Phonetic Alphabet

A Alfa
B Bravo
C Charlie
D Delta
E Echo
F Foxtrot
G Golf
H Hotel
I India
J Juliet
K Kilo
L Lima
M Mike
N November
O Oscar
P Papa
Q Quebec
R Romeo
S Sierra
T Tango
U Uniform
V Victor
W Whiskey
X X-ray
Y Yankee
Z Zulu

For the Air Force vocabulary, visit:
http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=7654 and
https://wwwmil.alsa.mil/mttps.html

Appendix 8: Internet Resources[4]

1.2. Respiration

http://www.faa.gov/pilots/training/airman_education/topics_of_interest/hypoxia/rem_hypoxia/index.cfm (hypoxia; 7Oct07)

1.7. Thermal Stress

http://www.cdc.gov/niosh/hhe/reports/pdfs/2000-0063-2907.pdf (Thermal stress resource; 8Oct07)

2.1. Constituents and Properties of the Atmosphere

http://history.nasa.gov/SP-367/chapt2.htm (aerodynamics of flight; 7Oct07)
http://www.lerc.nasa.gov/WWW/K-12/airplane/sound.html (speed of sound; 7Oct07)
http://www.adl.gatech.edu/classes/dci/aerodesn/dci03aero.html (aerodynamics of flight; 7Oct07)
http://www.cpc.ncep.noaa.gov/products/stratosphere (stratospheric filtering of UV radiation; 7Oct07)

2.2. Gas Laws

http://chemed.chem.purdue.edu/genchem/history/boyle.html (Boyle's Law; 7Oct07)
http://www.nndb.com/people/278/000049131/ (Dalton's Law; 7Oct07)
http://chemed.chem.purdue.edu/genchem/history/dalton.html (Dalton's Law; 7Oct07)
http://chemed.chem.purdue.edu/genchem/history/charles.html (Charles Law; 7Oct07)
http://chemed.chem.purdue.edu/genchem/history/gaylussac.html (Gay Lussac's Law; 7Oct07)
http://www.grc.nasa.gov/WWW/K-12/airplane/glussac.html (Charles and Gay Lussac's Law; 7Oct07)
http://www.ctie.monash.edu.au/hargrave/timeline1.html (Charles and Gay Lussac's Law; 7Oct07)
http://www.chm.davidson.edu/ChemistryApplets/GasLaws/index.html (Gas Laws; 7Oct07)
http://www.nndb.com/people/674/000096386/ (Henry's Law; 7Oct07)
http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/relhum.html (relative humidity; 7Oct07)

3.2. Hypoxia

http://www.usariem.army.mil/download/highmountain.pdf (hypoxia; 7Oct07)
http://mtp.jpl.nasa.gov/notes/altitude/altitude.html (altitude definitions; 8Oct07)
http://www.faa.gov/pilots/training/airman_education/topics_of_interest/hypoxia/rem_hypoxia/index.cfm (FAA hypoxia info; 8Oct07)
http://www.bordeninstitute.army.mil/published_volumes/harshEnv2/harshEnv2.html (Medical Aspects of Harsh Environments, Volume 2)
http://bordeninstitute.army.mil/published_volumes/mpmVol1/PM1ch25.pdf (Chapter 25. Military Medicine of the above military medicine text)

3.4. Trapped Gas

http://www.faa.gov/other_visit/aviation_industry/designees_delegations/designee_types/ame/media/Section%20II.1.4%20Trapped%20Gases.doc (Frenzel & Valsalva maneuvers; 8Oct07)

3.5. Factors Affecting Incidence of DCS

https://atiam.train.army.mil/soldierPortal/atia/adlsc/view/public/9621-1/fm/3-04.301/ch2.htm#s6p3 (FM 3-04.301 *Aeromedical Training for Flight Personnel,* 2-152; 9Oct07)
http://www.e-publishing.af.mil/shared/media/epubs/AFI11-403.pdf (AFI 11-409, Aerospace Physiological Training Program with cross-reference to ACCI 11-459 in Chapter 8 Pressure Suit Training; 9Oct07)
http://www.army.mil/usapa/epubs/pdf/r95_1.pdf (AR 95-1, Aviation Flight Regulations; 9Oct07)

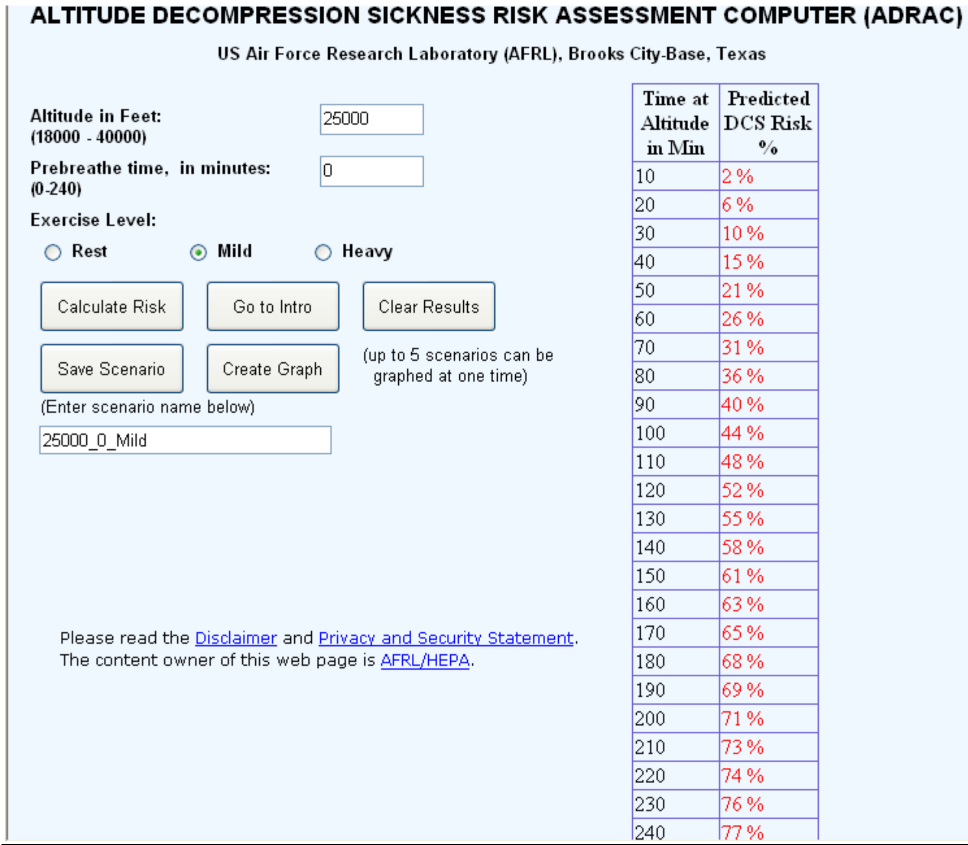
3.5. Altitude DCS Risk Assessment Computer (ADRAC) Model

http://biodyn1.wpafb.af.mil/altitude/login/Login.aspx?ReturnUrl=%2faltitude%2fDefault.aspx (ADRAC registration/login; 7Oct07)

The ADRAC model is available via the Air Force Research Laboratory. User registration must be completed and a username/password established via the web site before the model can be accessed.

[4] urls are shown with topic number/title and last date checked in parentheses.

Once logged into the AFRL Aircrew Performance and Protection Data Bank site, clicking on the ADRAC button and Go To Lab Program button will display the screen shown in Figure A8-1 (sans table on the right). Entering the altitude, prebreathe time, and exercise level followed by clicking Calculate Risk will result in update of the screen with a table like the one shown in Figure A8-1 with time at altitude and predicted DCS risk throughout the exposure time available. A chart that shows the level of risk throughout the exposure time available may be obtained by clicking Create Graph as shown below (Fig A8-2).



Time at Altitude in Min	Predicted DCS Risk %
10	2 %
20	6 %
30	10 %
40	15 %
50	21 %
60	26 %
70	31 %
80	36 %
90	40 %
100	44 %
110	48 %
120	52 %
130	55 %
140	58 %
150	61 %
160	63 %
170	65 %
180	68 %
190	69 %
200	71 %
210	73 %
220	74 %
230	76 %
240	77 %

Figure A8-1. ADRAC Prediction of DCS Risk at 25,000 ft with No Prebreathe and Mild Exercise

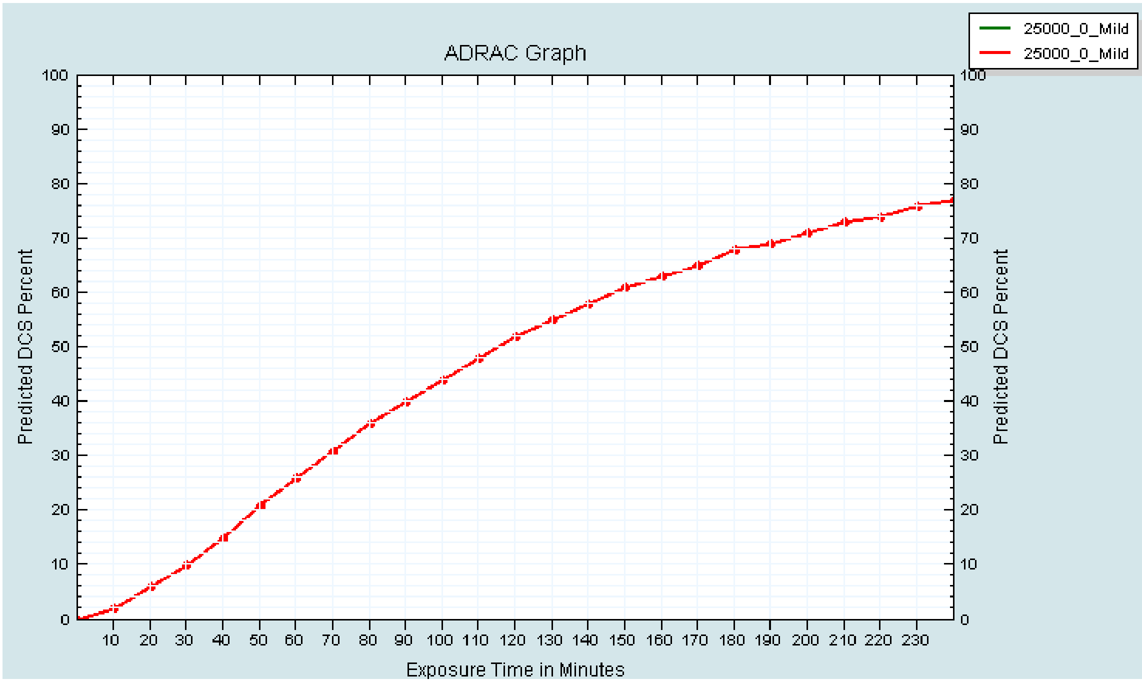


Figure A8-2. ADRAC Graph of DCS Risk at 25,000 ft with No Prebreathe and Mild Exercise

4.2. Self-Medication

National Center for Complimentary and Alternative Medicine:
http://nccam.nih.gov/health/herbsataglance.htm.
USAF Policy Letter on Nutritional Supplements:
https://kx.afms.mil/kxweb/dotmil/file/web/ctb_010712.pdf;jsessionid=BF4DE1D36113C80FC52C787C4670FB4D
USAF Policy Letter on the Use of Ephedra Containing Nutritional Supplements:
https://kx.afms.mil/kxweb/dotmil/file/web/ctb_012653.pdf;jsessionid=8C00D0A4D2FB4D1D2A450150C09DB879
SF 600 Overprint for review of nutritional supplements:
https://kx.afms.mil/kxweb/dotmil/file/web/ctb_023891.pdf
Aircrew Medication List and Over the Counter Medication List:
https://kx.afms.mil/aersopacemedicine

4.1. Crew Resource Management

http://www.airweb.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/0/80038cf51aace53686256e24005cbb23/$FILE/AC120-51e.pdf (FAA source; 7Apr08)

4.2. Nutrition

http://www.faa.gov/library/reports/medical/hop/media/topics_issues.pdf (health of pilots; 8Oct07)
http://www.fitness.gov/exerciseweight.htm (diet, exercise expenditures; 8Oct07)
http://airforcemedicine.afms.mil/idc/groups/public/documents/afms/ctb_016299.pdf (Aviation Nutrition Guide, 2003; excellent review and tables; 8Oct07)
http://dietary-supplements.info.nih.gov/Health_Information/Dietary_Reference_Intakes.aspx (Water and electrolyte guidance; 26Jun08)
http://www.e-publishing.af.mil/shared/media/epubs/AFI40-104.pdf (AFI 40-104. Nutrition Education.)

4.2. Human Performance

http://www.coloradofirecamp.com/swiss-cheese/introduction.htm (Human Error)

4.2. Smoking and Alcohol

http://www.airpower.maxwell.af.mil/airchronicles/aureview/1979/may-jun/bronson.html (Airpower article, well documented; 25Feb09)
http://www.cdc.gov/tobacco/data_statistics/sgr/sgr_2004/chapters.htm (Surgeon General's 2004 report on the health consequences of smoking; 24Feb09)
http://legacy.library.ucsf.edu/tid/qzx62f00 (report on Smoking : Its adverse effects on airline pilot performance)

4.3. Fatigue and Fatigue Countermeasures References

http://www.caa.co.uk/docs/33/CAAPaper2005_04.pdf (Civil Aviation Authority. *Aircrew Fatigue: A Review of Research Undertaken on Behalf of the UK Civil Aviation Authority*. CAA PAPER 2005/04, Research and Safety Analysis Section, Safety Regulation Group, October 2005; 9Oct07)
http://faid.interdynamics.com/ (Fatigue Audit InterDyne (FAID); 9Oct07)
http://www.sleepfoundation.org (National Sleep Foundation website; 9Oct07)

5.2. Oxygen Systems

http://www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=99b (NFPA 99B source site; 8Oct07)

Use of oxygen for breathing and prebreathing in chambers carries a risk of producing an atmosphere of increased burning rate as defined by the National Fire Protection Association (NFPA) Publication 99B (2005). The NFPA 99B, Standard for Hypobaric Facilities (2005;3.3.3.3), defines an atmosphere of increased burning rate based on a 12-mm/s burning rate (at 23.5% oxygen at 1 ATA). The equation defining such an atmosphere (NFPA 99B Chapter 3 Definitions; 3.3.3.3) is:

$$23.45/(\text{total pressure in atm})^{0.5}$$

= NFPA max O_2% without being an atmosphere of increased burning rate (see Table A8-1 for examples).

Table A8-1. Examples of Maximum Oxygen Concentrations without Being Atmospheres of Increased Burning Rate

Altitude (ft)	P_T (mmHg)	P_T (psia)	$TP_{atmospheres}$	NFPA Max O_2 (%)
0	760.1	14.7	1.000	23.4
5,000	632.4	12.2	0.832	25.7
8,000	564.6	10.9	0.743	27.2
10,000	522.8	10.1	0.688	28.3
15,000	428.6	8.3	0.564	31.2
17,500	387.3	7.5	0.510	32.9
25,000	282.3	5.5	0.371	38.5
30,000	225.4	4.4	0.297	43.1
35,000	178.9	3.5	0.235	48.3
40,000	141.2	2.7	0.186	54.4

7.3. Spatial Disorientation

http://www.faa.gov/pilots/training/airman_education/topics_of_interest/spatial_disorientation/index.cfm (FAA AC No: 120-51E on CRM; 7Apr08)

7.4. Motion Sickness

http://www.stens-biofeedback.com/about_biofeedback.html (Stens Corp. web site; 9Oct07)
http://www.bordeninstitute.army.mil/published_volumes/harshEnv2/harshEnv2.html (Medical Aspects of Harsh Environments, Volume 2)
http://www.bordeninstitute.army.mil/published_volumes/harshEnv2/HE2ch35.pdf (Chapter 35. Motion Sickness of the above text on military medicine)
http://www.flixxy.com/aerobatic-flight.htm (aerobatics video showing head movements of performers)

7.5. Impact and Ejection

http://www.aeromuseum.org/aircraft_b58.html

7.7. Laser Awareness Training

http://www.acc.af.smil.mil/xr/A8D/a8dr.htm (Laser Information Training and Education (LITE) training program, Aircrew Laser Eye Protection Specifications, etc.
http://www.a3a5.hq.af.smil.mil/a5r/a5re/docs/directedeneregy.htm (Directed Energy Task Force (DETF); historical information about lasers and the DE Roadmap offers guidance and boundaries for more detailed roadmaps; Eye Protection Task Force
http://www.naic.wrightpatterson.af.smil.mil/Documents/HANDBOOK/SXX00097/HTML/usthreat_pagetable.shtml (NASIC- home of the classified threat documents; Air Capstone Threat; Laser Threats to Aircrew – Worldwide; AFTTP 3-1 Vol I Chapter 12)
http://www.naic.wrightpatterson.af.smil.mil/Views/aws/DEW/lasers.html (Directed Energy Counter Adversary Action Group (DECAAG)
http://www.decaag.af.smil.mil.html (DECAAG website; a collection of documents on DE written by aircrew at the USAF Warfare Center)
http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA464670&Location=U2&doc=GetTRDoc.pdf (based on FM 8-50)

Glossary, Abbreviations, Acronyms, and Definitions

http://www.hq.nasa.gov/office/hqlibrary/aerospacedictionary/aerodictall/a.html (NASA Glossary; 11Dec07)
http://www.cpc.noaa.gov/products/outreach/glossary.shtml#Z (NWS Glossary; 11Dec07)
http://www.ofcm.gov/fmh3/text/appendg.htm (Office of the Federal Coordinator for Meteorology Glossary; 11Dec07)
http://www.azdot.gov/aviation/library/MP_PDF/1G4_MP_APP_B.pdf (Arizona Department of Transportation; 11Dec07)
http://www.y12.doe.gov/library/acronyms/letter.php?index (Department of Energy National Security Complex acronyms; 11Dec07)
http://www.nationalmuseum.af.mil/factsheets/factsheet.asp?id=7654 (Air Force Vocabulary; 26Mar08)
http://www.af.mil/shared/media/document/AFD-060726-020.pdf (USAF Long Range Strike Aircraft White Paper; Glossary)
http://www.e-publishing.af.mil/shared/media/epubs/AFI11-290.pdf (AFI11-290 Glossary on CRM; 7Apr08)
http://www.e-publishing.af.mil/shared/media/epubs/AT-M-06A.pdf (Glossary on CRM; 7Apr08

Appendix 9: Original Course Objectives

Atmosphere, Respiration, and Circulation

1. Describe the basic composition and functions of the atmosphere. Handbook 2.1
2. Describe the changes in pressure and temperature as each relates to altitude. Handbook 2.1
3. State the basis for MSL, AGL, and pressure altitude. Handbook 2.1
4. Describe the physiological zones of the atmosphere. Handbook 2.1
5. Describe the physiological significance of the following gas laws: Boyle's, Henry's, Gay-Lussac, Dalton's, and the Law of Gaseous Diffusion. Handbook 2.2
6. Describe the primary structures and functions of the respiratory system. Handbook 1.2
7. Describe how breathing rate and depth are controlled. Handbook 1.2
8. Describe the primary structures and functions of the cardiovascular system. Handbook 1.1
9. Describe how gases are transported in the cardiovascular system. Handbook 1.1

Vision

1. Identify the structure and function of the visual system. Handbook 1.4
2. Describe the physiological and anatomical blind spots. Handbook 1.4
3. Describe how vision affects balance, orientation, and situational awareness. Handbook 1.4 & 7.3
4. Describe photopic, mesopic, and scotopic vision. Handbook 1.4
5. Describe visual cues including visual fields and depth perception. Handbook 1.4
6. Describe a proper day and night scanning technique. Handbook 1.4
7. Describe common day/night time visual illusions and the conditions that lead to them. Handbook 1.4
8. Identify visual limitations that affect vision in both day and night flying operations. Handbook 1.4
9. Recognize the physiological impact of using night vision devices (NVDs). Handbook 1.4 & 6.1

Unaided Night Vision

1. Define night vision threats/limitations and safe measures to enhance situational awareness at night. Handbook 1.4
2. Describe the process of dark adaptation. Handbook 1.4
3. Identify how night vision is affected at higher altitudes. Handbook 1.4 & 3.2
4. Identify the operational impact of the anatomical and physiological blind spots. Handbook 1.4
5. Describe the diamond scanning technique. Handbook 1.4
6. List factors causing visual illusions and identify methods to counteract the illusions. Handbook 1.4 & 7.3
7. Describe autokinesis and practice methods used to prevent this illusion. Handbook 1.4 & 7.3
8. Describe the Purkinje shift phenomenon. Handbook 1.4
9. Describe the effects that bright light has on unaided night vision and how to preserve night vision. Handbook 1.4

10. The following objectives are applicable to pilots and navigators:
    a. Describe the causes and prevention of false horizons. Handbook 7.3
    b. Describe the causes and prevention of the glide slope illusion. Handbook 7.3

Physiological Effects of Altitude

1. Define and understand the 4 types of hypoxia and select a cause for each. Handbook 3.2
2. Recognize the objective and subjective signs and symptoms of hypoxia. Handbook 3.2
3. Define effective performance time (EPT) and time of useful consciousness (TUC) and the factors that affect an individual's EPT. Handbook 3.2
4. Describe the corrective procedures for treating hypoxia. Handbook 3.2
5. Define and understand the various causes of hyperventilation. Handbook 3.2
6. Describe the signs and symptoms of hyperventilation and how they differ from hypoxia. Handbook 3.2
7. Describe the corrective procedures for treating hyperventilation. Handbook 3.2
8. Identify why the treatment procedures for hypoxia and hyperventilation are the same. Handbook 3.2
9. Recognize which areas of the body are affected by trapped gases and determine how each is affected by ascent or descent. Handbook 3.4
10. Describe preventative measures for avoiding in-flight trapped gas problems. Handbook 3.4
11. Identify symptoms of trapped gases, when the symptoms are most likely to occur, and how to treat symptoms. Handbook 3.4
12. Define and understand the cause of decompression sickness (DCS). Handbook 3.5
13. Identify the symptoms of the four common types of DCS. Handbook 3.5
14. Describe the prevention and treatment of DCS. Handbook 3.5

Pressure Breathing

1. Describe what positive pressure breathing is and why it is required with ascent to altitude. Handbook 3.2
2. Describe the correct procedure for pressure breathing. Handbook 3.2

Cabin Pressurization

1. Identify the definition and purpose of cabin pressurization. Handbook 5.1
2. Describe how cabin pressurization works on an aircraft. Handbook 5.1
3. Identify and recognize the two types of schedules for a cabin pressurization system. Handbook 5.1
4. Identify the advantages and disadvantages of cabin pressurization systems. Handbook 5.1
5. Recognize the causes of cabin decompression in reference to the five factors affecting the equalization of a decompression. Handbook 5.1
6. Define and recognize the two types of aircraft decompressions along with the physical and physiological indications. Handbook 5.1
7. Describe the emergency procedures during an aircraft decompression. Handbook 5.1

Oxygen Equipment

1. Identify safety precautions used in handling and storage of oxygen equipment. Handbook 5.2
2. Identify oxygen requirements for crewmembers flying in pressurized and unpressurized aircrafts. Handbook 5.2
3. Describe the characteristics of different types of oxygen storage and delivery systems Handbook 5.2
4. Explain the purpose and use of pressure demand vs. continuous flow systems. Handbook 5.2
5. Describe the characteristics and operations of the narrow panel regulator. Handbook 5.2
6. Describe the characteristics and components of various oxygen masks. Handbook 5.2
7. Describe the characteristics and components of various connector assemblies. Handbook 5.2
8. Describe the purpose and use of the HGU-55/P helmet. Handbook 5.2
9. Describe the characteristics and operation of various emergency oxygen systems and equipment. Handbook 5.2
10. Describe proper care of the mask and helmet. Handbook 5.2
11. Describe procedures to accomplish a PRICE check. Handbook 5.2

Oxygen Lab (not tested)

1. Demonstrate safe handling practices of oxygen equipment.
2. Practice putting on the helmet, oxygen mask, and connector assembly and check for proper connections.
3. Practice performing PRICE check.
4. Practice operating the narrow panel regulator and go through each setting.
5. Practice the use of the pressure demand portable unit and emergency oxygen cylinder assembly system.
6. Describe how to refill and purge the pressure demand portable unit.
7. Practice putting on the headset and MBU 10/P oxygen mask and check for proper connections.
8. Practice emergency procedures using both personal oxygen equipment and the MBU 10/P oxygen mask.
9. Practice how to properly disconnect and set the regulator on post-flight configuration.

Noise and Vibration

1. Identify the structure and function of the auditory system. Handbook 1.5
2. Identify the characteristics of sound and how a characteristic contributes to hazardous noise exposure. Handbook 1.5
3. Describe the difference between the two basic types of hearing loss (conductive vs. sensorineural). Handbook 1.5
4. Identify the effects of hazardous noise and the protective measures used to minimize exposure. Handbook 1.5
5. Identify the characteristics of vibration and the symptoms that may result from prolonged exposure to aircraft vibration. Handbook 7.2

Acceleration

1. Identify and define the types of G-forces. Handbook 7.1
2. Identify the physical factors determining the effects of increased G-force on a crewmember's body. Handbook 7.1
3. Identify the physiological effects of positive and negative G-forces on a crewmember's body. Handbook 7.1
4. Describe characteristics of G-induced loss of consciousness (G-LOC). Handbook 7.1
5. Identify the elements of the anti-G straining maneuver (AGSM) and their relation to each other. Handbook 7.1
6. Identify common errors in performing the AGSM. Handbook 7.1 & 6.2
7. Identify the methods used to increase a crewmember's tolerance to positive G-force. Handbook 7.1
8. Describe operational methods used to maintain spinal health under G-forces. Handbook 7.1

Principles of Cockpit/Crew Resource Management and Situational Awareness

1. Describe the elements of crew resource management (IAW AFI 11-290). Handbook 4.1
2. Describe how situational awareness (SA) can be used to optimize performance in the context of the operational environment. Handbook 4.5
3. Describe the mechanisms of human information processing and how each affects performance. Handbook 4.2 & 4.5
4. Identify attention management problems, inappropriate motivations, and hazardous attitudes that detract from SA. Handbook 4.5
5. Describe methods of recovery from loss of SA. Handbook 4.5
6. Given a mishap scenario, select the attention management problems, inappropriate motivations, and hazardous attitudes contributing to loss of SA. Handbook 4.5

Stress and Fatigue

1. Describe how stress influences performance in the operational environment. Handbook 4.2
2. Describe the physiological mechanisms underlying fatigue. Handbook 4.3
3. Describe how fatigue is exhibited in the operational environment. Handbook 4.3
4. Describe circadian rhythms and circadian desynchronization. Handbook 4.3
5. Describe sleep hygiene and alertness management strategies for preventing and combating fatigue. Handbook 4.3

Fitness & Nutrition, Self-Medication, and Alcohol & Tobacco

1. Describe the impact of self-medication, alcohol, and tobacco use in the operational environment. Handbook 4.2
2. Distinguish the differences between the body's nutritional requirements for short-duration vs. prolonged operations. Handbook 1.6
3. Discuss the fitness components of flexibility, muscle strength, muscle endurance, and cardiovascular endurance as applied to the operational environment. Handbook 1.6

Hydration and Thermal Stress

1. Explain the physiological impact of dehydration on performance. Handbook 1.7
2. Describe the signs and symptoms of dehydration and how to prevent it. Handbook 1.7
3. Describe the physiological responses to thermal stressors and their impact on performance in the operational environment. Handbook 1.7
4. Describe how to prevent and treat thermal stress in an operational environment. Handbook 1.7

Laser Awareness

1. Describe the characteristics of the four types of lasers. Handbook 7.7
2. Describe the biological effects and potential safety hazards of laser exposure. Handbook 7.7
3. Describe the protective equipment available and what factors should be considered when determining the type of laser eye protection to use. Handbook 7.7

Human Factors of Escape, Egress, and Crash Survival

1. Describe considerations to take prior to ejecting out of the aircraft. Handbook 7.5 & 7.6
2. Describe considerations to take prior to unaided escape out of the aircraft. Handbook 7.5 & 7.6
3. Describe ways to improve your survivability before, during, and after a crash. Handbook 7.5 & 7.6
4. Describe proper body positions during a crash to minimize injury. Handbook 7.5 & 7.6
5. Describe hazardous situations inside and outside the aircraft that can impede escape and survival. Handbook 7.5 & 7.6
6. Describe the purpose of the preflight brief information and how this information can increase your chances of survival. Handbook 7.5 & 7.6
7. Describe proper use of personal gear, survival vests, kits, and manuals. Handbook 7.5 & 7.6
8. Describe potential hazards associated with crew doors, hatches, and canopies in transport and fighter aircraft. Handbook 7.5 & 7.6
9. Discuss post-crash actions related to physical stressors and mental state of mind. Handbook 7.5 & 7.6
10. Describe proper fit, adjustment, and use of parachute harness. Handbook 7.5 & 7.6
11. Describe physiological threats of aided/unaided egress. Handbook 7.5 & 7.6

Type 4A Chamber Flight (not tested)

1. Describe the physiological effects of pressure change. Explain, recognize, and treat for hypoxia symptoms in self and others. Handbook 3.2
2. Describe and practice proper oxygen discipline.
3. Describe visual problems resulting from decreased oxygen during night flight operations. Handbook 1.4 & 3.2
4. Describe and practice the use of the emergency oxygen cylinder assembly and pressure demand portable unit.
5. Describe how to prevent, recognize, and treat hyperventilation. Handbook 3.2
6. Describe and perform pre-flight, in-flight, and post-flight oxygen equipment checks.

Appendix 10: Organizations of Potential Interest to USAF Aerospace Physiologists

Aerospace Medical Association (AsMA)

http://www.asma.org/

From their Bylaws:

VISION, MISSION, AND GOALS

A. Vision: The international leader in aviation, space, and environmental medicine.

B. Mission: Apply and advance scientific knowledge to promote and enhance health, safety, and performance of those involved in aerospace and related activities.

C. Definition: As used in this document, aerospace medicine is the multi-disciplinary application of professional and scientific knowledge, training, and research to promote and maintain the health, well-being, safety, and performance of those involved in aerospace activities.

D. Goals:

(1) Provide governance of the Association to maintain a sound financial structure and ensure continuity of the Association.
(2) Provide opportunities for education and promote research.
(3) Provide members opportunities for professional growth and development.
(4) Represent the discipline of aerospace medicine to professional, commercial, and governmental organizations and advocate policies and standards.

Publication: *Aviation, Space and Environmental Medicine*

Certification in Aerospace Physiology is available by examination

Human Factors and Ergonomics Society (HFES)

http://www.hfes.org/web/Default.aspx

From their website:

The Human Factors and Ergonomics Society is dedicated to the betterment of humankind through the scientific inquiry into and application of those principles that relate to the interface of humans with their natural, residential, recreational, and vocational environments and the procedures, practices, and design considerations that increase a human's performance and safety at those interfaces.

Publication: *Human Factors: The Journal of the Human Factors and Ergonomics Society*

Certification in Human Factors is available by examination

Undersea and Hyperbaric Medical Society (UHMS)

http://uhms.org/

From their Constitution:

This Society shall be international in scope. Its primary purposes shall be:

1. to provide a forum for professional scientific communication among individuals and groups involved in basic and applied studies concerned with life sciences and human factors aspects of the undersea environment and hyperbaric medicine.
2. to promote cooperation between the life sciences and other disciplines concerned with undersea activity and hyperbaric medicine.
3. to develop and promote educational activities and other programs, which improve the scientific knowledge of matters related to undersea and hyperbaric environments and the accepted applications of hyperbaric oxygen therapy for the membership, as well as physicians and allied health professionals, divers, diver technicians and the public at large.
4. to provide a source of information and support in the clinical practice of hyperbaric medicine and to stay abreast of legislative, legal, and regulatory changes in the field.
5. to provide a means by which hyperbaric facility directors/owners will have an opportunity to request an accreditation survey of their facility for safety, staffing and verifying the adequacy of the professional medical application of hyperbaric therapy.

Publication: *Undersea and Hyperbaric Medicine Journal*

Certification in Hyperbaric Technology is available by examination

SAFE Association

http://safeassociation.com/

From their website:

Objective: The primary objective of the SAFE Association is to stimulate research and development in the fields of safety and survival and to disseminate pertinent information to concerned individuals in government and industry. In addition, the objective is to establish and maintain a meaningful relationship between the SAFE Association and the scientific communities related to safety and survival.

The SAFE Association is dedicated to the preservation of human life. It provides a common meeting ground for the sharing of problems, ideas, and information.

SAFE, a non-profit professional association headquartered in Oregon, maintains chapters throughout the world. It boasts an international group of members.

Membership is not restricted by academic background, experience, or specialty. SAFE members represent the fields of engineering, psychology, medicine, physiology, management, education, industrial safety, survival training, fire and rescue, human factors, equipment design, and the many subfields associated with the design and operation of aircraft, automobiles, buses, trucks, trains, spacecraft, and watercraft. Individual and corporate members include equipment manufacturers, college professors and students, airline flight attendants, government officials, pilots, and military life support specialists. This broad representation provides a unique meeting ground for basic and applied scientists, the design engineer, the government representative, the training specialist, and the ultimate user/operator to discuss and solve problems in safety and survival.

Publication: *SAFE Journal*; Symposium Proceedings; SAFE News

American College of Sports Medicine (ACSM)

http://www.acsm.org/AM/Template.cfm?Section=About_ACSM

From their website:

Mission: The American College of Sports Medicine promotes and integrates scientific research, education, and practical applications of sports medicine and exercise science to maintain and enhance physical performance, fitness, health, and quality of life.

Publication: *Sports Medicine Bulletin*

Certification in several sub-specialties is available by examination

Society for Human Performance in Extreme Environments (HPEE)

http://www.hpee.org

From their website:

The Society for Human Performance in Extreme Environments (HPEE) was created to inspire and facilitate collaboration between researchers, practitioners, and other professionals to improve human safety and performance in extremely risky and challenging settings.

Publication: *Journal of Human Performance in Extreme Environments*

Board of Certified Safety Professionals

http://www.bcsp.org/bcsp/index.php?option=com_frontpage&Itemid=1

The principal purposes of the BCSP, as more fully set forth in its Articles of Incorporation, are to:

A. Establish the minimum academic and experience requirements necessary to receive certification as a Certified Safety Professional, the designation of Associate Safety Professional, or other such designations established pursuant to resolution by the Board of Directors.
B. Determine the qualifications of applicants and arrange, control, and conduct investigations and examinations to verify the qualifications of candidates for certificates to be issued by the BCSP
C. Grant and issue to qualified applicants a certificate and maintain a directory of the holders of all valid certificates.
D. Establish requirements for the continuance of certification. The BCSP also has such powers as are now or may hereafter be granted by the General Not-For-Profit Act of the State of Illinois and determine compliance of certificate holders with approved requirements.
E. Represent its certificate holders in communication and, where appropriate, in negotiations with public and private agencies, groups, and individuals with respect to matters of common interest; and it will inform employers, specifiers, public officials, the public, and engineering and related practitioners of the benefits of certification.

Certified Safety Professional is available by evaluation examination.

Appendix 11: Contributors' Biographies

1. William B. Albery, Ph.D.
   Dr. Bill Albery is a 36-year civilian in the U.S. Air Force and technically manages the Wright-Patterson AFB centrifuge facility as biomedical engineer and deputy branch chief for the Air Force Research Laboratory. He has a B.S. in systems engineering from Wright State University (1971), an M.S. in biomedical engineering from Ohio State University (1976), and a Ph.D. in biomedical sciences from Wright State (1987). Bill received the Paul Bert Award from the Aerospace Physiology Society of the Aerospace Medical Association (2004) and serves as an Assistant Clinical Professor in the School of Medicine at Wright State.

2. Quentin D. Bagby,Maj, USAF, BSC
   Quentin "Q" Bagby is the Chief, USAF Aerospace Physiology Training Program at NAS Pensacola, FL. His 25 years of experience in the AETC undergraduate flying training arena include serving as Executive-Level Courseware Developer and Program Manager. After graduating as a Distinguished Graduate from both Commissioned Officer Training and Aerospace Physiology Officer's courses, he became an aerospace physiologist in 2000 at Moody AFB. He helped usher in a new era of flying training with the T-6A Texan II and was directly involved in developing the Airsickness Management Program, from its inception in the mid 1980s to the program of today.

3. Neal Baumgartner, Ph.D.
   Dr. Neal Baumgartner is an exercise physiologist currently serving in AETC to improve and maintain optimal physical training of USAF battlefield airmen. He also serves as subject matter expert to HQ AF for the AF Fitness Program including research and development of the new 2010 fitness test standards. Dr. Baumgartner served as an active duty aerospace physiologist retiring in 2001. He has a B.S. degree in biology from the USAF Academy and M.S. and Ph.D. degrees in exercise physiology from the University of New Mexico and the University of Texas at Austin, respectively.

4. James W. Brinkley
   Mr. Brinkley is the former director of the Human Effectiveness Directorate of the Air Force Research Laboratory. Since graduating from Ohio State University in 1958, he performed research on impact acceleration effects and protection technologies. He is the author of 78 journal articles, technical reports, and numerous book chapters on impact acceleration, windblast, and protection technologies. He is a Fellow of Aerospace Medical Association. His numerous awards include the Association's Eric Liljencrantz Award and the John Paul Stapp Award for his accomplishments in biodynamics, and induction into the International Safety and Health Hall of Fame of the National Research Council.

5. Mary T Brueggemeyer, Col, USAF, MC, SFS
   Col Brueggemeyer received an M.D. degree from the University of Louisville in 1992. She completed residency training in general surgery and served as staff surgeon at Dyess AFB, TX, from 1997-1999. Dr. Brueggemeyer entered aerospace medicine in 2001 and has served as Flight Medicine Flight Commander, Moody AFB, GA, from 2001-2004; Director of the Department of Instructional Programs, Defense Medical Readiness Training Institute at Ft. Sam Houston, TX, from 2004-2006; and Commander, 355 Aerospace Medicine Squadron, Davis-Monthan AFB, AZ, from 2006-08. She received an MPH in 2009 and completed a Residency in Aerospace Medicine at USAFSAM in 2010.

6. John R. Buhrman, M.S.
   Mr. Buhrman is a biomedical engineer with the Biomechanics Branch of the Human Effectiveness Directorate of the Air Force Research Laboratory at Wright-Patterson AFB. His M.S. degree is from Wright State University. Mr. Buhrman has conducted research in the areas of paraplegic gait modeling and human biodynamic response to impact acceleration, the effects of neck loading due to weighted helmet systems, and the evaluation of spinal injury risk during aircraft ejection. He leads the Performance and Safety Team of the Biomechanics Branch, administrates the AFRL Biodynamics Data Bank, and is a member of the Wright Site IRB.

7. Eric Chase, Lt, USAF, BSC
   Lt Eric Chase earned a B.S. in physiological sciences from the University of Arizona in 1998. He entered graduate school in 2001 at the University of Washington Medical School to study physiology & biophysics. After earning an M.S. degree in 2004, he moved to a village in Africa to teach with the Peace Corps. He returned in 2007 and entered Commissioned Officer Training in May of 2008 and became an aerospace & operational physiologist with the U.S. Air Force later that year. He is currently assigned to Randolph AFB Aerospace & Operational Physiology Training Flight.

8. Jennifer L. Davis
   Ms. Davis is a mechanical engineering student from Miami University in Oxford, OH, working as a summer hire for the Human Effectiveness Directorate of AFRL. She was a research assistant on several biomechanics research efforts supporting the Biomechanics Branch. Her work included conducting tests involving human subject research to ascertain comfort and fatigue over extended periods of time. She was also involved in compiling pilot ejection injury statistics and conducting impact injury literature searches as part of her completion of a B.S. degree in mechanical engineering.

9. Steve Dawson, Maj, USAF, BSC
   Steve "Lenny" Dawson is Chief, USAF Initial Flying Training Curriculum and formerly the deputy director of the USAF NVG Academic Instructor Course at Randolph AFB. He has 19 years of experience in aircrew performance. He served 11 years as an aircrew life support technician, technical school and NVG mobile training instructor, and CDC writer. In 2000, he was commissioned an aerospace physiologist, assigned to Euro-NATO Joint Jet Pilot Training at Sheppard AFB. More recently, he worked as program manager/physiology consultant for aircrew life support equipment at Brooks City-Base, followed by an assignment at the USAF School of Aerospace Medicine. He has an M.S. in biomedical sciences from Colorado State University.

10. Lee Diekmann (MSgt, USAF, Ret)
    MSgt Diekmann was the Superintendent of Hyperbaric Medicine Branch, Wilford Hall Medical Center, Lackland AFB, TX, prior to his retirement. During his first assignment in aerospace physiology at Beale AFB, CA, he became the supervisor for launch and recovery of U-2 and SR-71 aircraft. During his next assignment at Vance AFB, OK, he became the lead instructor in motion sickness training for the 71st FTW. He conducted student training using biofeedback to increase their relaxation and skills and improve their ability to avoid motion sickness. His following assignment at Brooks City-Base involved supervision of aerospace physiology courses where college credit was given.

11. William R. Ercoline, Lt Col, USAF (Ret)
    Bill is the San Antonio area manager for Wyle Integrated Science and Engineering Group. He's a former USAF C-130 pilot and AETC instructor pilot in the T-41, T-37, and T-38 aircraft. Bill was an assistant professor of physics at the USAF Academy from 1978-82. Since 1988, he has conducted numerous research studies in the areas of spatial disorientation countermeasures and aviation-related human factors issues for AFRL at Brooks City-Base, TX, improving flight symbology for reducing pilot workload in low-visibility conditions. He recently developed flight training profiles for AETC's ground-based SD trainers and provides teaching support to USAFSAM.

12. Paul W. Fisher, Col, USAF, BSC
    Colonel Paul Fisher is the Commander, AF Office of Scientific Research and formerly the Senior Military Professor, Biology Department, USAFA. He received his B.S. in biology from the University of Miami, M.S. in zoology from Montana State University, and Ph.D. in cell biology from Duke University. He has served as an aerospace physiologist for the high-altitude reconnaissance and airdrop programs and an instructor at USAFSAM and led high-altitude and acceleration physiology and advanced oxygen systems research at AFRL. Colonel Fisher completed the Clinical Hyperbaric Physiology Fellowship and is a recipient of the Paul Bert Award for Aerospace Physiology Research. He is board certified in both aerospace physiology and hyperbaric technology.

13. David R. Jones, Col, USAF, MC, CFS (Ret)
Dr. Jones completed residency in aerospace medicine, later serving at Myrtle Beach AFB, Nha Trang AB, Torrejon AB, and Randolph AFB, logging nearly 2000 hours (286 combat) in 35 aircraft types. After completing psychiatry residency, he served at the Neuropsychiatry Branch, Clinical Sciences Division, USAFSAM. His military awards include the Legion of Merit (1-OLC), Bronze Star, and Air Medal (3-OLC). He was editor-in-chief of *Aviation, Space, and Environmental Medicine* from 1987-1996 and is currently Clinical Professor of Psychiatry at the USUHS. Dr. Jones is a member of the IAASM and a Fellow of the ACPM, AsMA, APA, and AHFA.

14. William D. Kosnik, Ph.D.
William Kosnik earned a Ph.D from Simon Fraser University in Vancouver, Canada, and is an engineering psychologist for the Human Performance Optimization Division of the 711th HPW. He's a human factors engineering expert implementing human systems integration solutions within Air Force acquisition programs. Dr. Kosnik worked for 21 years as a vision scientist for AFRL's Directed Energy Optical Radiation Branch. He conducted force protection program research on directed energy effects for visual function and air crew performance, designed computational models of optical radiation visual effects, and developed laser-based optical technologies.

15. Robert M.Lindberg, M.A.
Robert M. Lindberg received his M.A. in management from Antioch University McGregor, and his B.S. in mathematics is from the University of Wisconsin. He is Chief of the Human Performance Optimization Division at the 711th Human Performance Wing, Human Performance Integration Directorate. He is responsible for the establishment of human systems integration within the AF. Robert has over 25 years of operational and acquisition experience in aerospace systems such as B-1, F-4, F-15, F-16, and F/A-18 E/F. His specialty areas are acquisition, aircraft engines, avionics, flight test, human systems integration, logistics, maintenance, manufacturing, and program management.

16. Valerie E. Martindale, Lt Col, USAF, BSC
Lt Col Martindale is the Human Performance Consultant, Air Force Human Systems Integration Office and Chair of the Air Force Human Performance Functional Area Working Group. Previously, she was Chief of the Human Performance Division on the Air Staff, Chief of Aerospace Physiology; Chief, International Human Factors for AFRL; and Chief of Altitude and Hyperbaric Research. Lt Col Martindale is a private pilot and board certified in aerospace physiology. She is a member of the Undersea and Hyperbaric Medical Society and the American Society for Cell Biology and is a Fellow of the Aerospace Medical Association.

17. Ryan W. Maresh, Maj, USAF, BSC, CAsP, Ph.D.
Maj Maresh is an Assistant Professor of Biology at the United States Air Force Academy. Previously, he was Chief, Aerospace & Operational Physiology Branch, U.S. School of Aerospace Medicine at Brooks City-Base, TX, where he oversaw training & education of new officer and enlisted accessions into the 43A and 4M0 career fields, as well as the aerospace physiology training of several other medical specialties. Prior assignments include AFIT at Colorado State University and working with the high-altitude reconnaissance program at Beale AFB, CA. He is board certified in aerospace physiology and is an Associate Fellow of the Aerospace Medical Association.

18. Andy McKinley, B.S.
Mr. McKinley received a B.S. in biomedical engineering from Wright State University and is pursuing a Ph.D. in human factors engineering. He works as a biomedical engineer at AFRL's Biobehavioral Performance Branch located at Wright-Patterson AFB, OH. Mr. McKinley is the Human Effectiveness Team Lead for the AFRL Rotary-Wing Brownout Solution Program. He is also exploring noninvasive transcranial stimulation techniques to improve human cognitive performance. Mr. McKinley's work has focused on modeling the effects of acceleration stress on physiologic and cognitive performance, use of multisensory displays for unmanned aerial systems, and use of eye metrics for monitoring human performance.

19. Richard L. McKinley, B.S., M.S.
Mr. McKinley is the principal acoustics engineer at AFRL's 711 HPW at WPAFB, OH. He received degrees in biomedical engineering and communications and digital signal processing from Vanderbilt University and AFIT. Mr. McKinley has led development of high-performance hearing protection, establishment of noise exposure criteria, measurement of intense noise fields, enhancement of voice communication performance, and development of 3-D auditory displays. Mr. McKinley is the USAF voting member for three ANSI-accredited standards committees and has over 150 publications in acoustics and noise. In 1996, he was elected Fellow of the Acoustical Society of America.

20. George Miller, M.S., Maj, USAF (Ret)
George Miller is a research engineer with the 711th Human Performance Wing, Brooks City-Base, TX. He has a B.S. degree in chemical engineering from Auburn University, Auburn, AL, and an M.S. degree in chemical engineering from Ohio State University, Columbus, OH. His areas of expertise are on-board oxygen generating systems (OBOGS) and aircraft oxygen systems safety-of-flight testing. He has numerous publications on oxygen generation technology and holds six U.S. patents. He is the USAF Co-Chair of the DoD Oxygen Standardization Coordinating Group and a member of the SAFE Association and the American Institute of Chemical Engineers.

21. James C. Miller, Ph.D., Maj, USAF (Ret)
James C. Miller, Ph.D., CPE, has over 30 years of experience in the measurement and analysis of human physical and cognitive performance in military and civil aviation; highway, rail, and maritime transportation; and night and shift work. He focuses mainly on reducing the effects of fatigue on productivity and safety, especially in 24/7 and night operations. Prior to undertaking his doctoral studies in 1971, Dr. Miller served as a C-130E Hercules tactical transport pilot in Vietnam. He logged 699 hours of combat time and was awarded the Distinguished Flying Cross and the Air Medal with four Oak Leaf Clusters.

22. Craig Olson, Lt Col, USAF, BSC (Ret)
Craig is the President of Salus Education, LLC in San Antonio and an independent contractor working for the American Dietetic Association, Office of Scientific Affairs and Research. He is a former navigator with over 1,000 hours in the KC-135. He graduated from the USAF Dietetic Internship in 1993 and received an M.S. degree in nutrition from the University of California, Davis in 2002. Craig has conducted research related to the performance-enhancing properties of specific food constituents. Among Craig's many assignments, he had the honor to serve as the commander of the Air Force's largest nutritional medicine squadron.

23. Mr. Brian Stanley
Brian Stanley received a B.S. in aeronautics from San Jose State University. Upon completion of Undergraduate Pilot Training, where he flew the T-37 and T-38, he then served in two Air National Guard units and flew the C-130 E/H aircraft. He is currently an airline pilot and has flown the Boeing 727, 757, and 767; the Fokker 100; and now the McDonnell Douglas MD80. He holds an FAA flight engineer certificate and an aircraft powerplant mechanic certificate. He is a Lieutenant Colonel and serves in the U.S. Air Force Reserves providing operational perspective to AFRL's Biobehavioral Performance Branch.

24. Ronald C. Tutt, Maj, USAF, BSC (Ret)
Ronald C. Tutt, OD, MS, FAAO, is on the USAF School of Aerospace Medicine faculty and is a published vision scientist. He has extensive clinical and aeromedical experience covering over 20 years of service to include research of altitude/centrifuge effects following refractive surgery and low-altitude NVG hypoxia; development/integration programs such as night vision devices, laser eye protection, head-mounted cueing systems, and aircrew chem/bio systems; as well as management of USAF aviation vision correction programs (contact lenses and spectacles). Dual qualified as optometrist and aerospace physiologist, Dr. Tutt serves as consultant/lecturer for U.S./international flight surgeons, optometrists, and aerospace physiologists.

25. Henning E. vonGierke, DEng.
Dr. von Gierke was a researcher and technical leader at Wright-Patterson AFB in the areas of biodynamics, sound, and vibration. His 40 years of work led to the development of human tolerance criteria for vibration and shock that were used as the basis for a comprehensive set of ISO safety and performance consensus standards for vibration exposure. His studies are documented in over 160 publications on noise exposure and its effects on biodynamics of human exposure to impact, crash, and on vibration loads, on vestibular effects, and protection against hazardous force environments.

26. James T. Webb, Ph.D., Maj, USAF (Ret)
Dr. Webb is a former USAF command pilot with >3900 hours in F-4D and C-141A aircraft. He received a Ph.D. from the University of Washington and became an Associate Professor of Biology at the USAF Academy in 1979. Later, he worked as an acceleration and altitude research scientist with USAFSAM at Brooks AFB, TX. After retirement, he served as a contracted senior scientist for AFRL, publishing 18, first-author, peer-reviewed research papers. Dr. Webb is board certified in aerospace physiology by the Aerospace Medical Association (AsMA), a Fellow of AsMA, and recipient of AsMA's Leverett Environmental Science Award in 1999.

27. Donald J. White, Col, USAF, BSC
Colonel White is the Biomedical Science Corps Associate Corps Chief for Aerospace Physiology. His operational career includes experience in acquisition, research, and education. He served as faculty at USAFSAM, aircrew training, operational physiology, and operational safety. He has been commander of an Airmanship Training Squadron, Aerospace Physiology Flight, and Aerospace Medicine Flight. He has participated on 14 Class A Safety Investigation Boards, including consultant to the Columbia Shuttle Accident Investigation Board and two Medical Incident Investigation Boards. Col White served two higher headquarters tours and is a HALO and Static Line Master Parachutist with over 4,000 parachute deployments.

28. Mark T. White, Capt, USAF, BSC
Captain White is a USAF aerospace physiologist and Chief, AP Operations Element at Brooks City-Base, TX. He has a B.S. in exercise science (1994) and an M.S. in exercise physiology (1999). His professional background is in work-related physical ability testing, application of occupational physiology, and collegiate coursework curriculum development and instruction. He served as an educator at CSU Sacramento, a UC Davis researcher, and a private-business co-owner. He is a member of the American College of Sports Medicine (ACSM) and has held ACSM Exercise Specialist and National Strength and Conditioning Association (NSCA) Certified Strength and Conditioning Coach certifications.

29. Andrew D. Woodrow, Lt Col, USAF, BSC
Lt Col Woodrow's 26 years in operational physiology and human factors touch every aspect of aerospace physiology from SR-71/U-2/TR-1 support to clinical hyperbaric medicine. He has expertise in underwater escape systems, extreme thermal stress performance, high-altitude life support OT&E, and sustained fatigue trials and participated in over 170 centrifuge runs. Lt Col Woodrow is a board certified hyperbaric technologist and ergonomics manager (CEM) and is a Fellow of the Aerospace Medical Association. He has been consultant to 10 Class A aircraft mishaps and several Class B investigations and has amassed over 350 hours in 14 aircraft types.